Department for
Water Resources

Impact of Farm Dams on Streamflow in the Upper Marne Catchment

Government of South Australia

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Department for
Water Resources

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DWR Adelaide Hills Farm Dams.

FOREWORD

South Australia's water resources are fundamental to the economic and social wellbeing of the State. Water resources are an integral part of our natural resources. In pristine or undeveloped situations, the condition of water resources reflects the equilibrium between rainfall, vegetation and other physical parameters. Development of surface and groundwater resources changes the natural balance and causes degradation. If degradation is small, and the resource retains its utility, the community may assess these changes as being acceptable. However, significant stress will impact on the ability of a resource to continue to meet the needs of users and the environment. Degradation may also be very gradual and take some years to become apparent, imparting a false sense of security.

Management of water resources requires a sound understanding of key factors such as physical extent (quantity), quality, availability, and constraints to development. The role of the Resource Assessment Division of the Department for Water Resources is to maintain an effective knowledge base on the State's water resources, including environmental and other factors likely to influence sustainable use and development, and to provide timely and relevant management advice.

Bryan Harris
Director, Resource Assessment Division
Department for Water Resources

GLOSSARY

Act – The Water Resources Act 1997 (South Australia)

Annual Adjusted Runoff - Annual runoff generated from a catchment with the impact of farm dams removed.

Baseflow -The water in a stream that results from groundwater discharge to the stream. (This discharge often maintains flow during seasonal dry periods and has important ecological functions.)

Catchment - A catchment is that area of land determined by topographic features within which rainfall will contribute to runoff at a particular point.

Catchment Area – The land area contributing surface water to the flow in a watercourse at a specific location. The catchments for major rivers are commonly defined to the point where the river flows into another larger river or the sea (or terminal lake), and will usually include a number of sub catchments for the tributary streams to that river. The Act defines catchment area to mean the area of a catchment water management board as identified by the proclamation establishing the catchment water management board.

Catchment Water Management Board – A statutory body established under Part 6, Division 3, s. 53 of the Act whose prime function under Division 2, s. 61 is to implement a catchment water management plan for its area.

Ecosystem – Any system in which there is an interdependence upon, and interaction between living organisms and their immediate physical, chemical and biological environment.

Geographic Information System (GIS) - Computer software that allows for the linking of geographic data (for example land parcels) to textual data (soil type, land value, ownership). It allows for a range of features, from simple map production to complex data analysis.

Ground water - Water occurring naturally below ground level or water pumped, diverted or released into a well for storage underground.

Hydrology - The study of the characteristics, occurrence, movement and utilisation of water on and below the earth's surface and within its atmosphere.

ML – Megalitre, which is equal to one million litres (1 000 000).

Model – A conceptual or mathematical means of understanding elements of the real world, which allows for predictions of outcomes given certain conditions. Examples include estimating storm runoff, assessing the impacts of dams or predicting ecological response to environmental change.

Sq. Km - Square Kilometre

State Water Plan – The plan prepared by the Minister under Part 7, Division 1, s. 90 of the Act.

Streamflow - The discharge that occurs in a natural channel**.**

Stream Gauging - The quantitative determination of streamflow using Gauges, Current Meters, Weirs, or other measuring instruments at selected locations.

Surface Water – (a) water flowing over land (except in a watercourse), (i) after having fallen as rain or hail or having precipitated in any other manner, (ii) or after rising to the surface naturally from underground; (b) water of the kind referred to in paragraph (a) that has been collected in a dam or reservoir.

Runoff - That portion of precipitation that moves from the land to surface water bodies.

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EXECUTIVE SUMMARY

Following the declaration of the Notice of Restriction within the Marne Catchment, the Department for Water Resources was assigned by the River Murray Catchment Water Management Board to undertake a study to assess the impact of farm dams on the surface water resources within the Upper Marne Catchment. Similar studies carried out for catchments in the area indicate a significant amount of annual runoff being trapped in the farm dams, resulting in reduction of runoff to the downstream sections of the catchments.

Computer modeling was used in this study to simulate the hydrological processes in the catchment, and to further estimate the impact of farm dams on streamflows. This report describes the outcomes of the study, the main findings of which are:

Rainfall Rainfall trends in the catchment indicate a wetter than average period between 1902 and 1924, a drier than average period 1925 and 1948, and no definite trend after that. However, rainfall records of the last 20 years indicate a reduction in the frequency of wetter years.

Runoff Runoff from the Upper Marne Catchment is highly variable, and also highly dependent on rainfall. The mean annual runoff for the catchment is considerably less than the mean annual runoff of other catchments in the Mount Lofty Ranges.

The Springton sub-catchment generates almost half of the runoff generated from the Upper Marne catchment, with the wetter sub-catchments of Springton, Western Slopes and Eden Valley (Figure 2) together generating 70% of the runoff generated from the whole catchment.

Farm Dams The storage capacity of farm dams in the Upper Marne Catchment has more than doubled between 1991 and 1999. As of 1999 data, there are 640 farm dams with a potential storage capacity of 2,400 ML. This total farm dam capacity has virtually reached the allowable limit of development (50% of median annual adjusted runoff) adopted in the regulated Mount Lofty Ranges catchments and referred to as a sustainability indicator in the State Water Plan 2000.

Farm dam developments in the individual sub-catchments of Western Slopes, Eden Valley and Keyneton have already exceeded the allowable limit of development. In the drier sub-catchments of Marne and Somme this limit is yet to be exceeded, but by only a few megalitres. Springton is the only sub-catchment where the current level of development is well below the allowable limit.

Impact of Farm Dams On Streamflow

The current level of farm dam development reduces the median annual adjusted runoff (runoff generated under a scenario without the impact of dams) by 18% at the mean and 24% at the median. If controls were not put in place and farm dam development continued at the current rate, the mean and median annual adjusted runoff would be reduced by 28% and 39% by the year 2009.

The impact of farm dams on annual runoff is very high during drier years and is marginal during wetter years, although the annual runoff is historically low during drier years. During a given year, the impact of farm dams is more significant during late summer / early wet season, when the dams are relatively empty and later, during late wet season / early summer, when pumping of water for irrigation starts. Though the runoff volumes and their reduction due to farm dams during summer is small, these small volumes may be crucial for the ecosystems downstream, particularly during dry years.

Farm dams also reduce the duration of low and medium runoff events, which are crucial for the groundwater recharge occurring in the immediate downstream area between Cambrai and Kongolia, and for the survival of the streamflow dependant ecosystems further downstream. If farm dam development continued at the current rate, a low rainfall (440 mm rainfall) year such as 1985 which generated streamflow in the past may not generate any streamflow in the future.

Farm dams seem to have a minimal impact on high flows (flows in excess of 10 ML/day). Hence flows large enough to reach the River Murray are possibly influenced more by climate variations.

Controls on Farm Dam Development

Springton: Controls on further farm dam development in the Springton sub-catchment is of highest priority. Future farm dam development is likely to occur more rapidly in the few remaining catchments that have no major on-stream dams. Further developments in these catchments would greatly reduce the current flows leaving the Upper Marne catchment.

Western Slopes, Eden Valley and Keyneton: Controls on farm development in the Western Slopes, Eden Valley and Keyneton sub-catchments are of next higher priority as the farm dam development in these sub-catchments have exceeded the allowable limit of development.

Marne and Somme: Controls in the drier sub-catchments of Marne and Somme are comparatively of low priority, as they are likely to develop less rapidly.

Hydrological Monitoring Well distributed rainfall data is one crucial input for effective hydrological modelling. Hence, rainfall data collection by private landholders at Eichler, Hillridge, Netherford and Roesler need to be continued and formalised.

Streamgauging needs to be continued at Cambrai, with further streamgauging at a minimum of two more sites. One of these should be sited on the Marne River upstream of the confluence of Marne and Somme rivers to delineate the flows from the two catchments. The other site should be located in the downstream portion of the Marne, to monitor the runoff reaching the River Murray.

This study confirms the results of previous studies conducted on the catchment. It can be concluded that continued farm development would further reduce the low and medium streamflows reaching the downstream users, particularly during dry years.

PURPOSE AND SCOPE OF THE STUDY

This report provides the basis for consideration of surface water management options for the Upper Marne River catchment. The scope of work of this study covers the following:

- Review previous studies on the catchment
- Quantify the surface water resources within the catchment
- Construct and calibrate a computer Rainfall–Runoff model for the catchment
- Assess the impact of farm dams on the streamflows
- Model different case scenarios to aid future catchment management decisions
- Identify data deficiencies and recommend future monitoring requirements

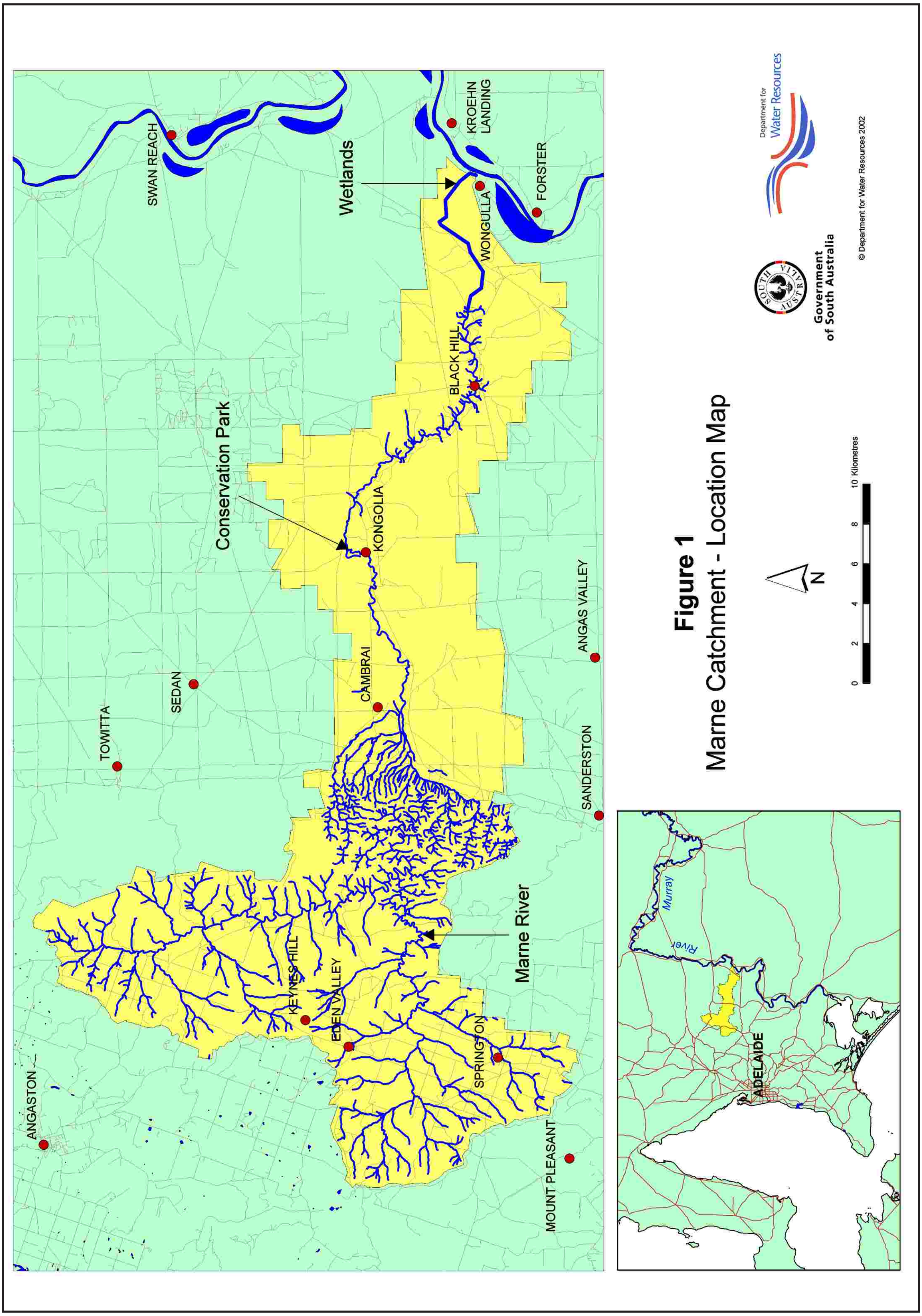

Figure 1
Marne Catchment - Location Map

BACKGROUND

Physical Setting

The Marne catchment is located approximately 80 kilometres north of Adelaide in the Mount Lofty Ranges (Figure 1). The main river in this catchment is the Marne River, which originates in the Mount Lofty Ranges and flows eastwards. The other river is the Somme River, which originates from the northern section of the catchment and joins the Marne River just before the Marne Gorge. The river then flows eastwards onto the River Murray plains before joining the River Murray approximately 30 kilometres downstream of Swan Reach. Streamflow is measured at a stream gauging station downstream of the Marne Gorge at a location 5 Km west of Cambrai. The catchment area of 240 Km^2 upstream of this gauging station is being considered for this study. Hence, "Catchment" in this study refers to the upper Marne catchment or the portion of the catchment upstream of the gauging station.

Management Arrangements

The River Murray Catchment Water Management Board has responsibility for managing the River Murray and its catchments. The rapid development of farm dams over the last two decades has raised considerable concern on the sustainability of water resources in the catchment. Surface water use in highlands and ground water use in the plains are vital to the economics of the region, but in recent years concerns have been raised as to the appropriateness of the high volumes of development given the impacts seen on the environment.

Previous Studies

Previous studies and investigations on the Marne catchment were reviewed; a summary of the findings of the studies is given below.

1. The Impact of Development on Streamflow in the Marne River (Good, 1992).

Relevant findings of this study were:

- The volume of water stored in the farm dams increased by 2.7 times between 1974 and 1992.

- Assuming the 1991 levels of development, the streamflow was estimated to have been reduced by 10% due to farm dams, for the period 1973-1988.

2. Inventory of Dams in the Marne Catchment (Billington, Kotz, 1999).

Relevant findings of this study were:

- The yield of the catchment has been greatly affected by the construction of farm dams.
- Both stock / domestic dams (<5 ML) and large dams (>50 ML) impact significantly on catchment yield and runoff throughout the Marne catchment.

3. Impact of Water Use in the Marne Catchment on Water Resources (BC Tonkin & Associates, 1998).

Relevant findings of the study were:

- The present level of farm dam construction (mostly in the high rainfall areas) is reducing flows by about 20% in an average year at Cambrai.
- Farm dams are significantly reducing downstream flows in dry years, although flows would be very low even for a natural catchment with no farm dams.
- The present level of development results in relatively small reductions to downstream flows during wet years.

4. The impact of farm dams on streamflows in the Marne Catchment (Nathan, 1999).

Relevant findings of the study, which are primarily based on trend analysis carried out using a Generalised Additive Model, were:

- An average annual decrease of observed streamflows of 44 ML/year; the trend being the result of changes in the relationship between rainfall and runoff, and being independent of any climatic changes.
- This decrease in streamflow is attributed wholly to the increase in farm dams and not as a result of associated land use changes.
- Trends indicate a direct correspondence between the volume of farm dam development and the decrease in streamflow, i.e. for every 1 ML of farm dam development there would appear to be a corresponding 1 ML decrease in streamflows. (For modelling purposes, it was assumed in this study that the total demand extracted each year from every farm dam was equivalent to its storage volume)

Context of this Study

Previous studies on the catchment used techniques that do not model the influence of farm dams in a spatially explicit manner. These techniques undertake the water balance computations for a specified number of farm dams, whose sizes are selected stochastically from the known distribution of farm dams in the catchment. These techniques are useful to estimate the overall impact of farm dams on a catchment but not the impact on an individual sub-catchment level.

As the conditions, viz., rainfall, land-use, concentration of farm dams, etc., are not uniform throughout the catchment, modeling the catchment with the actual spatial representation of the dams provides a more accurate picture of the impact of the individual dams. Representation of dams in a spatially explicit manner during the modeling process enables:

- assessment of the influence of the individual larger controlling dams on a sub-catchment level,
- representation of the catchment as a series of smaller sub-catchments based on the location of the larger controlling dams,
- identification of the sub-catchments that are still at a low level of development (‘free-to-flow’ sub-catchments) in comparison to those that are fully developed, and
- development of management options for the extent and distribution of future farm dam development, and more importantly, the operating mechanisms of existing dams at the sub-catchment level.

Realising the above-mentioned advantages of modeling at a sub-catchment level the River Murray Catchment Management Board commissioned the Department for Water Resources to carry out this study.

Further details on the modeling technique used, construction and calibration of the model, modeling case scenarios and the results are explained in the following sections of this report.

HYDROLOGY

Rainfall

Rainfall in the Marne catchment varies from 810 mm in the western highlands to 350 mm in the eastern side of the catchment. Rainfall data from 6 stations were used to represent the rainfall distribution in the catchment. The data for these are from three different sources:

1. Bureau of Meteorology – Daily rainfall records at Keyneton (023725), from 1884 to 1997.

2. Department for Water Resources – Daily Rainfall Records at Mount Adam (AW 505537), from 1973 to 1996.

3. Private Landholders – Yearly data at Eichler, Hillridge, Netherford and Roesler. Rainfall data collected by private landholders is available for 9 locations. The duration of the data varies from 4 years to 78 years.

Double Mass Curve analysis was performed between Keyneton and the neighboring stations in the Mount Lofty Ranges to test regional homogeneity of the data and to fill data for missing periods.

As daily data at the private stations was missing for considerable periods, the yearly data from these stations were compared with the data available from Keyneton and Mount Adam. Based on their correlation, daily data was derived for the four private stations and was used along with the data available from Mount Adam and Keyneton.

Based on the rainfall distribution, the upper Marne catchment was sub-divided into 6 sub-catchments (Figure 2). The 6 subcatchments and the average annual rainfall for them are shown in Table 1.

NO.	Sub-catchment	Source for Rainfall data	Average Annual Rainfall (mm)
1	Western Slopes	Mount Adam (AW505537)	810 mm
2	Springton	Roesler (Private)	707 mm
3	Eden Valley	Hillridge (Private)	573 mm
4	Keyneton	Keyneton (BoM023725)	527 mm
5	Marne	Eichler (Private)	520 mm
6	Somme	Netherford (Private)	446 mm

Table 1: Average Annual Rainfall for the sub-catchments in the Upper Marne

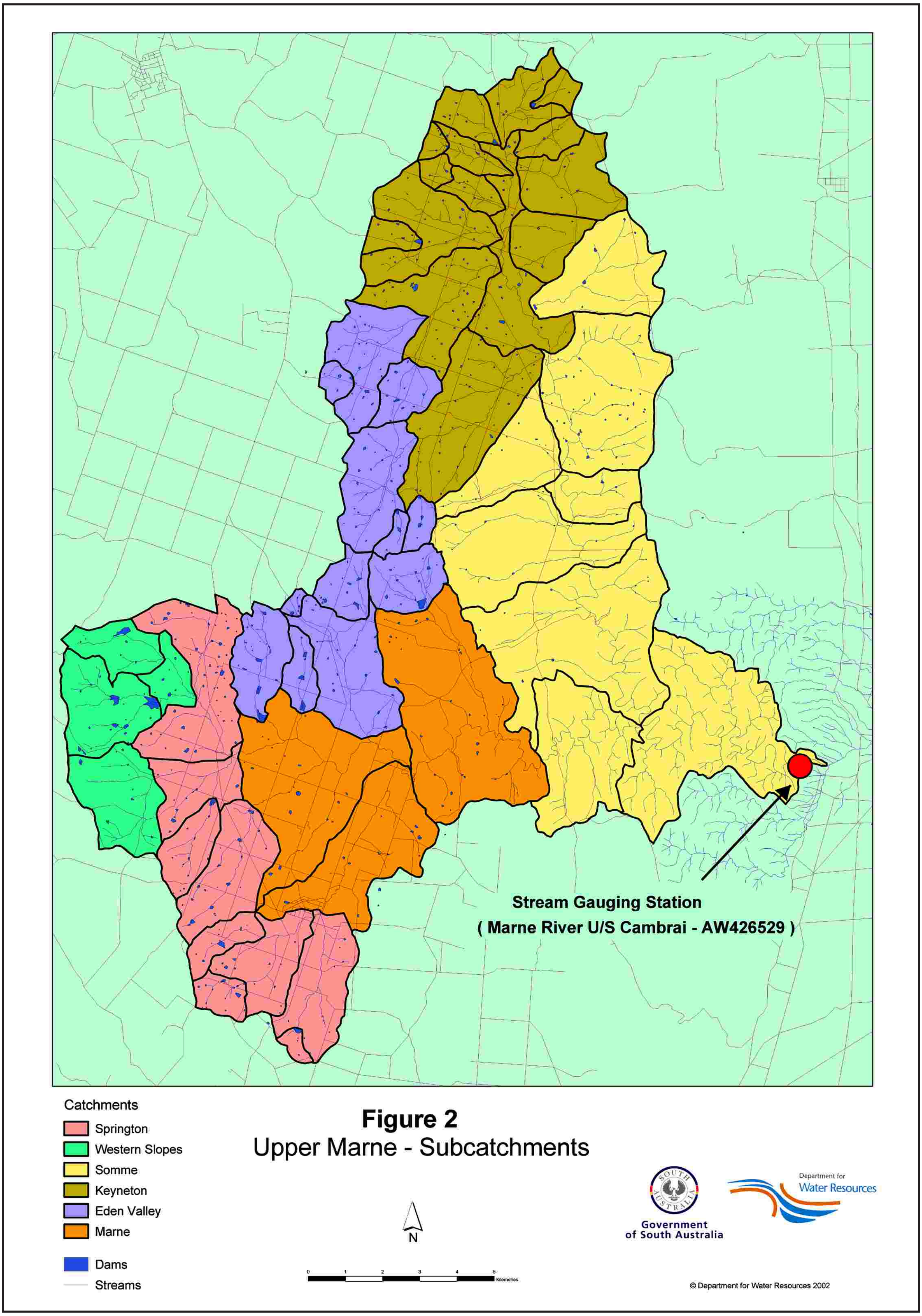

Figure 2
Upper Marne - Subcatchments

The trendline for the annual rainfall at Keyneton (Figure 3) shows a overall decreasing trend, which is an indication of reducing rainfall over the time period (1884-1997). To confirm this falling trend further analysis was carried out using a residual mass curve method and trend analysis.

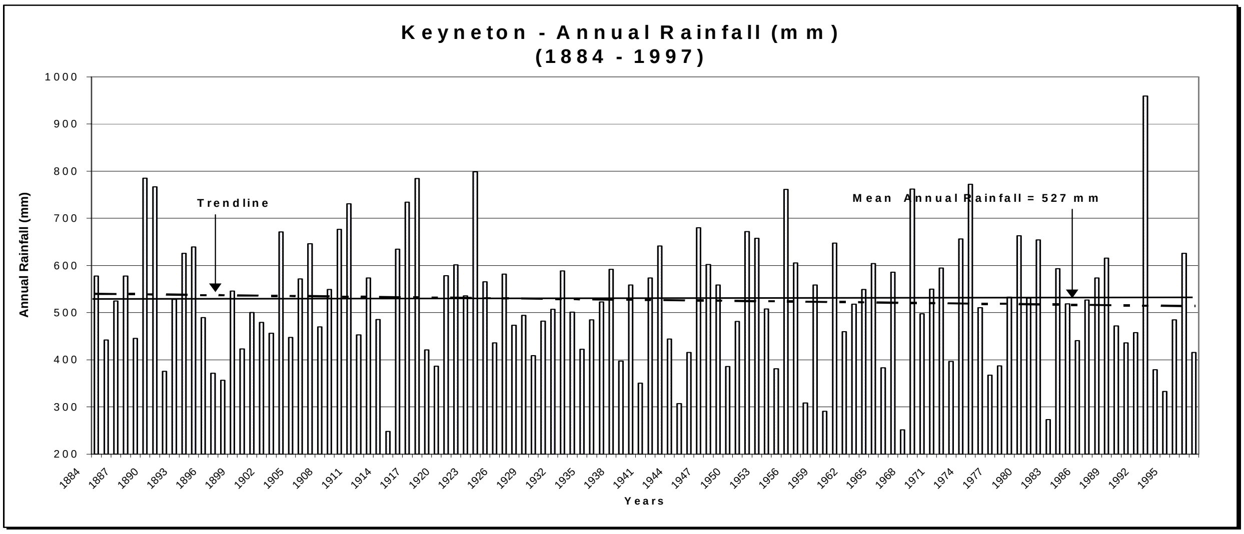

Figure 3. Annual Rainfall at Keyneton

A residual mass curve is used as a tool to identify wetter and drier periods from rainfall records. A distinctive upward slope indicates a wetter than average period and vice versa.

The residual mass curve (Figure 4) for the rainfall records at Keyneton suggests a wetter than average period between 1902 and 1924, and drier than average period between 1924 and 1945. From 1945 onwards there is no clear indication, but a random period of wet and dry years.

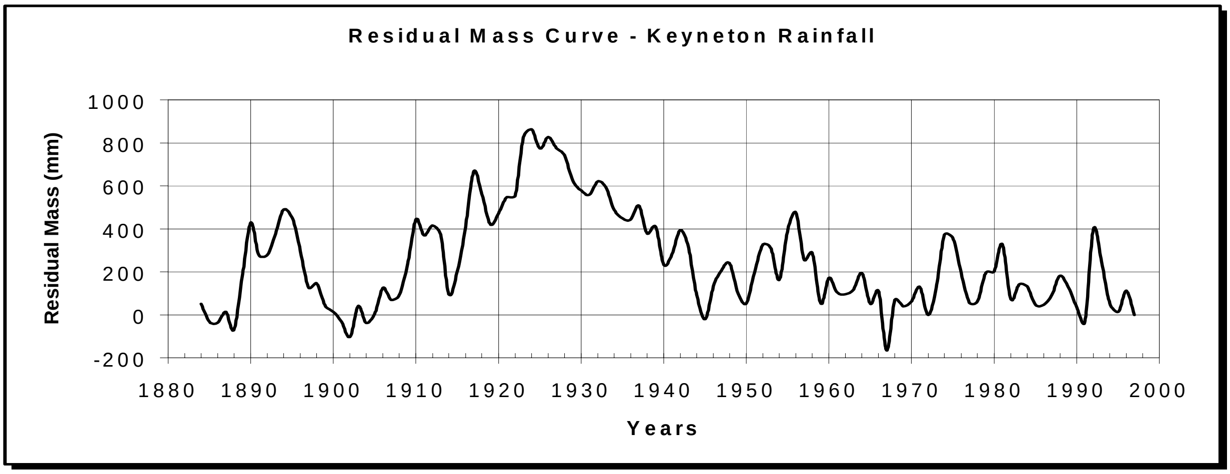

Figure 4. Residual Mass Curve for Rainfall Records

Trend analysis methodologies are used to obtain definite trends in data. One such methodology, the Mann's test (Grayson, 1996) was used for further analysis of rainfall trends. The results of the trend analysis indicate that there is no trend for the rainfall records from 1884 to 1997 at 95 % significance level. But at lower levels of significance the trends are similar to the trends in the residual mass curve.

However, inspection of the last 20 years of rainfall records at Keyneton (Figure 3) indicate a reduction in the frequency of wetter years (years recording above average annual rainfall).

Streamflow

Streamflow is measured at the Stream Gauging Station AW426529, 5 Km west of Cambrai on the Marne River. Continuous streamflow records are available at this station from 1972 to 1988. From 1989, data is either incomplete or not available.

The annual flows of the catchment (Figure 5) show a high degree of variability, ranging from 33,533 ML in 1974 to 80 ML in 1982. The mean (7,710 ML) and the median (4,774 ML) were calculated from the years with complete data sets. The mean flow of 7,710 ML or 32 mm is considerably less than the average flow for most of the Mount Lofty Ranges (Clark, 1987).

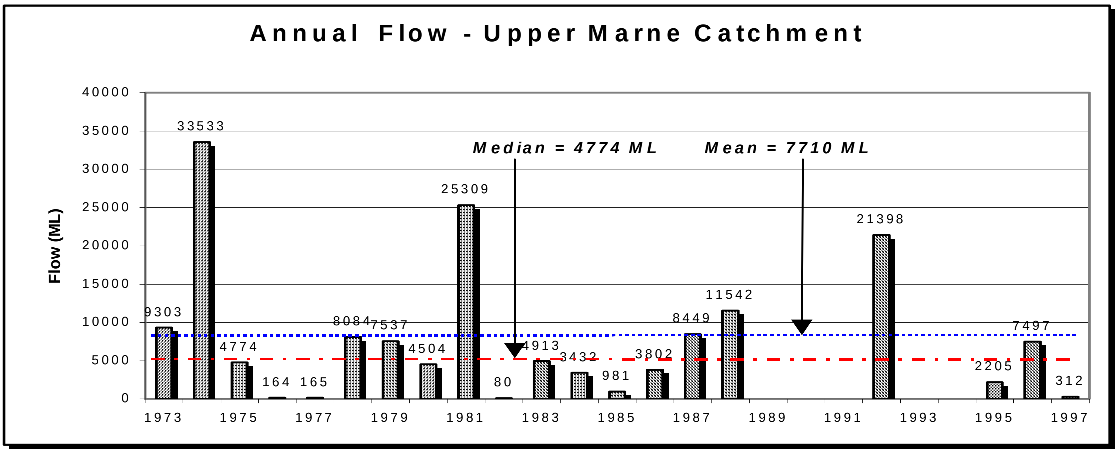

Figure 5. Annual Flow - Upper Marne Catchment

The flow frequency curve (Figure 6) plotted for the daily flows at Cambrai between 1973 and 1987 indicates that in an average year

- a flow of 0.1ML/day or higher would occur only during 150 days,
- a flow of 10 ML/day or higher would occur only during 63 days, and
- a flow of 50 ML/day or higher would occur only during 24 days.

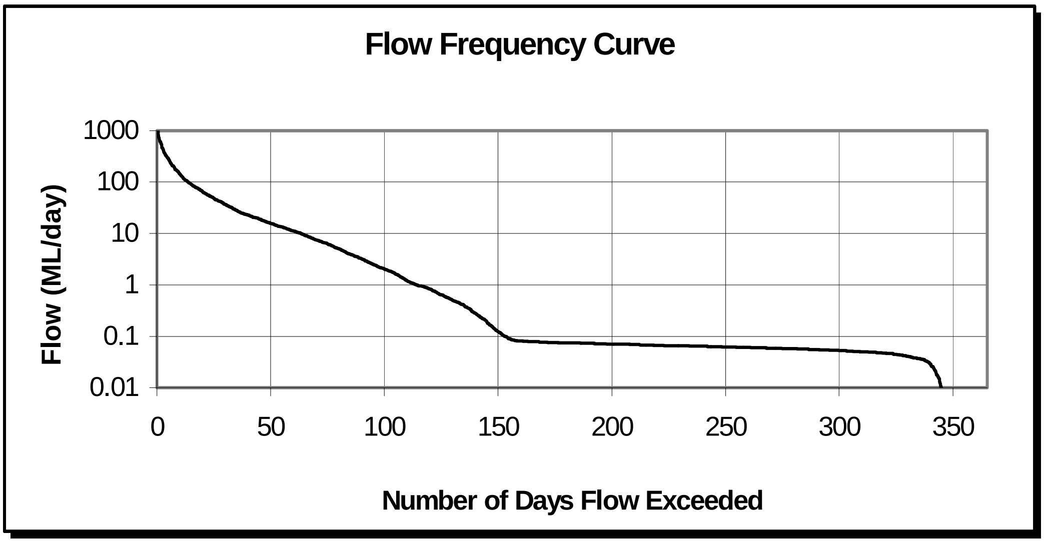

Figure 6. Daily Flow Frequency Curve – Cambrai

Rainfall – Runoff Relationship

A rainfall-runoff relationship for the catchment (Figure 7) indicates that a rainfall of 600 mm and above is required at Keyneton to generate runoff equal to the mean annual runoff, and 550 mm of rainfall to generate runoff equal to the median runoff. Both these rainfall values are higher than 527 mm, which is the annual average rainfall at Keyneton. During the 20-year period from 1977 to 1997 the annual rainfall equaled or exceeded the average rainfall only during 9 years (Figure 3). And, during this 20-year period, the only period that had a sequence of a few above-average rainfall years was between 1978 and 1982. The rest of the above-average rainfall years during this 20 period were preceded by drier (below average) years.

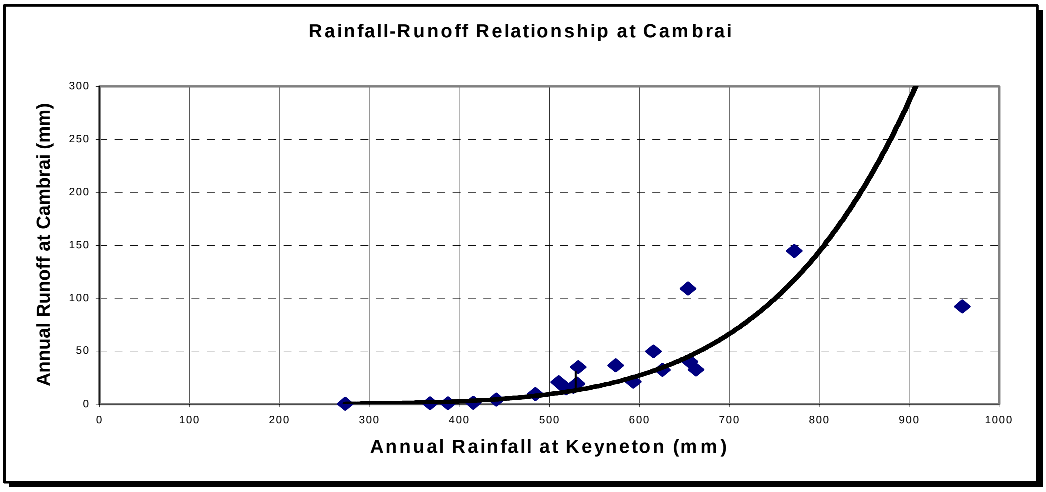

Figure 7. Rainfall Runoff Relationship

The hydrological data sets (1973 to 1997) used for this study indicate:

- a good temporal distribution of rainfall data, as it includes a few near average rainfall years (1975, 1980), a few good wet years (1992, 1996) and a few good dry years (1982, 1994). But in comparison to the 115 years of rainfall data available at Keyneton the 15-year data set used for this study represents a drier than average rainfall. (Figure 3)

- a reasonable spatial distribution of rainfall stations, though four of the six stations used for this study are privately operated and the data from them needs further verification.

- a high degree of variability of the streamflow data and its high dependence on rainfall. (Figure 5)

- the consistency in the rainfall-runoff relationship for the period 1973 to 1988, which provides a good base for calibration of the rainfall-runoff model. (Figure 7) Inconsistent and incomplete streamflow data restricted the usage of data after 1988.

- The dependence on groundwater of the base flows generated from the area downstream of the Marne Gorge and upstream of the gauging station.

FARM DAMS

The development of large farm dams for irrigation purposes in the last two decades is mainly attributed to intense agricultural development, particularly vineyards, in the higher rainfall areas in the western highlands.

Farm dams information was obtained from the aerial surveys conducted in 1991, 1996 and 1999 which were then digitised for further use in the Department for Water Resources's Geographic Information System. This information from aerial surveys was then verified by field surveys conducted by the Department for Water Resources in 1999. The farm dam volumes were calculated using the dam surface area-volume relationship developed by McMurray (McMurray, 1996).

The total number of dams in each of the 6 sub-catchments and their details are shown in Table 2 and Table 3.

Tables 2 & 3. Farm Dam Details of Upper Marne Catchment

Sub-Catchment	Area (Km^2)	Number of Dams in 1999	Dam Volume (ML)
Western Slopes	15	42	723
Springton	33	144	431
Eden Valley	32	131	689
Marne	38	66	158
Keyneton	46	163	314
Somme	76	94	117
Total	**240**	**640**	**2433**

	Dam Size Class							
Sub-Catchments	< 0.5 ML	0.5 – 2 ML	2 – 5 ML	5 – 10 ML	10 – 20 ML	20 – 50 ML	> 50 ML	**Total**
Western Slopes	11	16	5	4	2	1	3	42
Springton	49	58	19	6	9	2	1	144
Eden Valley	34	52	20	10	8	4	3	131
Marne	19	26	12	6	2	1	0	66
Keyneton	38	96	21	3	3	2	0	163
Somme	33	45	11	4	1	0	0	94
Total	**184**	**293**	**88**	**33**	**25**	**10**	**7**	**640**

The development of large farm dams is concentrated in the high rainfall areas of Western Slopes, Springton and Eden Valley. Seventy percent of the total dam volume is located in these areas, which together make up only one-third of the total area of the catchment. Of these the Western Slopes are the most controlled accounting for 30% of the total dam volume from an area totalling only 7% of the catchment. This catchment also contains many of the largest dams in the region.

The rate of farm dam development is shown (in Table 4) by the comparison of the results of the annual aerial surveys.

Table 4. Comparison of Dam Volumes (ML) - 1991 and 1999

Sub-Catchment	1991	1999
Western Slopes	259	723
Springton	227	431
Eden Valley	329	689
Marne	62	158
Keyneton	164	314
Somme	81	117
Total	**1123**	**2433**

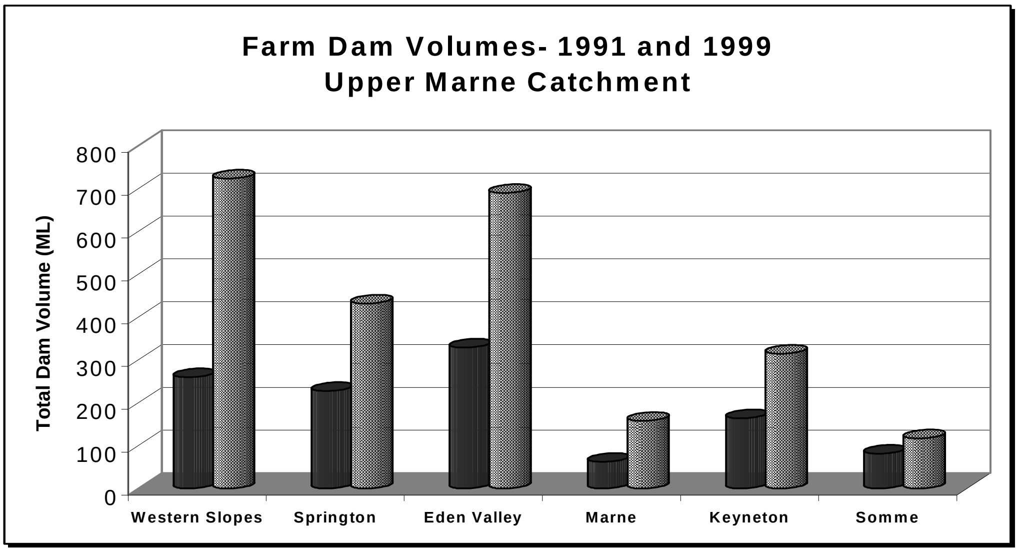

Figure 8. Comparison of Farm Dam Volumes – 1991 and 1999

As indicated in Table 4 and Figure 8:

- Farm dam volumes have increased significantly between 1991 and 1999 in all the sub-catchments except for Somme.
- The total farm dam volume has more than doubled between 1991 and 1999.
- The higher rainfall areas of Western Slopes, Springton and Eden Valley show a considerable increase in farm dam volumes, with the highest increase in the Western Slopes sub-catchment.
- The increase in dam volume can be attributed equally to an increase in both, large and small dams within the catchment.

SURFACE WATER MODELLING

The surface water model was constructed using a PC based water balance-modeling platform, WaterCress (Cresswell, 2000). The rainfall-runoff relationship was modeled using the AWBM Model (Boughton W, 1996) (Appendix A).

Model Construction

The upper catchment was first divided into 6 sub-catchments (Western Slopes, Springton, Eden Valley, Marne, Keyneton and Somme) based on differing rainfall zones (Figure 2). The next stage was to sub-divide each of these sub-catchments into smaller catchments. The major criteria for sub-division was the presence of a significant on-stream farm dam ('controlling dam'), which is deemed to control or block the flow of the catchment area upstream. There may also be other smaller farm dams present in the sub-catchment, which may not control the flow to the extent to which the major dam does. Confluence with adjacent tributaries was also a factor in the division factor. Based on these factors, each sub-catchment is either:

1. a catchment area of a controlling dam with other smaller dams upstream, if any, or

2. a catchment area of a series of controlling dams with other smaller dams upstream, if any, or

3. in the absence of controlling dams, a catchment area of a stream with off-stream dams, or

4. a similar catchment area of a stream to those above with no dams.

The sub-division of a sub-catchment into smaller catchments based on the above-mentioned criteria is illustrated for the Western Slopes sub-catchment in Figure 9. All the sub-catchments used in the model are shown in Figure 2.

The sub-catchments were then digitised and incorporated into a GIS (ArcView 3.2) to calculate the areas of the sub-catchments and the volume of farm dams present in them (Appendix B).

Each of these sub-catchments is represented in the model as a catchment node followed by an on-stream dam node (sub-catchments without farm dams will not have the dam node) (Figure 9). The on-stream dam node represents the accumulation of all the dams in the sub-catchment. The whole catchment is represented as a series of these nodes that are connected based on the drainage pattern (Appendix C).

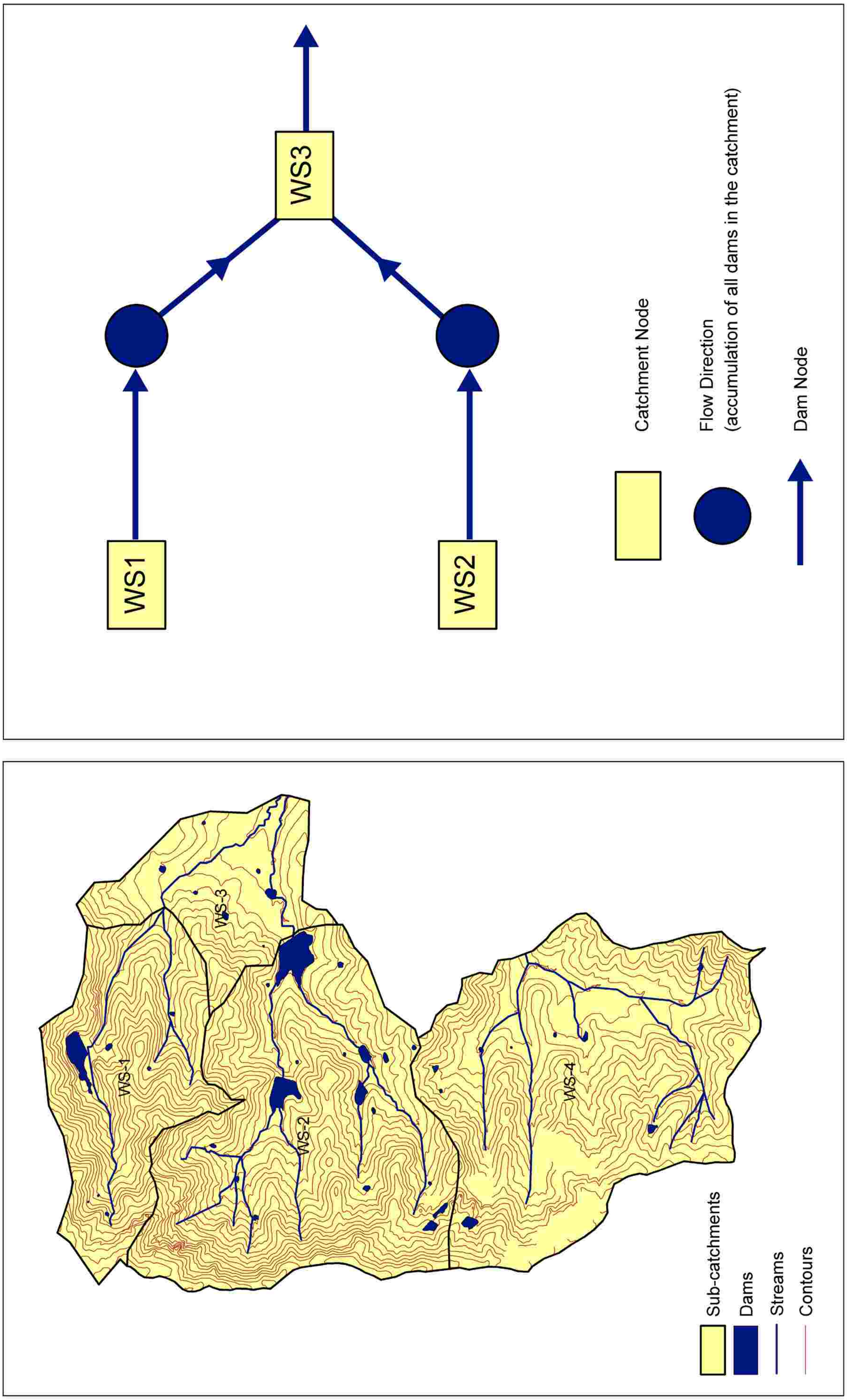

Figure 9

Western Slopes Subcatchment

Sub-division into smaller catchments and setup of catchment nodes in the model

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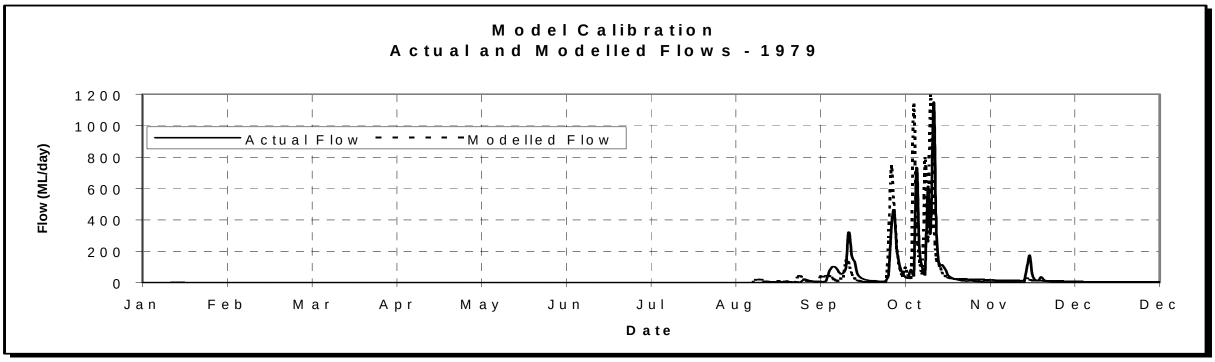
Model Calibration

The model was calibrated using daily runoff data from Cambrai for 14 years starting from 1975. Rainfall data from Keyneton (for Keyneton sub-catchment) Mount Adam (for Western Slopes sub-catchment), Roesler (for Springton sub-catchment), Eichler (for Marne sub-catchment), Hillridge (for Eden Valley sub-catchment) and Netherford (Somme sub-catchment) were used. The soil characteristics and land use were assumed to be uniform throughout the catchment. Due to lack of water usage information the annual water usage from the farm dams was assumed to be 30% of the storage capacity. This rate of water use allows some carry over of storage to following years and is assumed to be the most appropriate option in this study as it provides for higher reliability of supply for permanent plantings. It should be recognised that if greater usage rates are being employed this may significantly increase the impacts identified in this report.

Calibration of the catchment involves iterative variation of the input parameters until a good correlation is obtained between the simulated runoff and the actual runoff. The correlation coefficient (Cv) values for annual and monthly data were 0.89 for annual data and 0.84 respectively.

The model simulated the monthly and annual runoff better than daily runoff. As with many hydrological models, it was difficult to simulate runoff for all the different rainfall conditions viz., dry, average and wet year. The model was calibrated for an average rainfall year, which tends to underestimate the runoff during some wet years. Simulation of runoff from summer thunderstorms, and low flows, particularly during the end of a runoff event were also difficult.



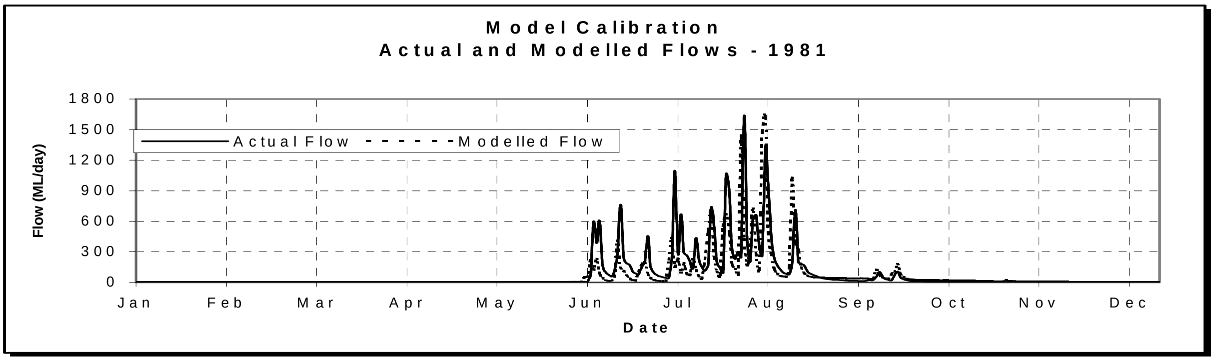


Figure 10. Rainfall-Runoff Model Calibration Plots

Modeling Case-Scenarios

Once the model is calibrated, runoff data can be generated for any period of available rainfall data and desired case-scenarios can be simulated for making water management decisions. The three case scenarios modeled for this study were:

- Pre-Development Scenario - Runoff with the influence of dams removed
- Current Scenario - Runoff with farm dam volumes raised to 1999 levels
- Future Scenario – Runoff in 2010 assuming farm dam development continued at current rate

The annual water usage from the farm dams was assumed to be 30% of the storage capacity in all the modelling scenarios.

Pre-Development Scenario - Runoff with the influence of farm dams removed

Runoff at the gauging station, measured during a period (1975 to 1988), includes the influence of farm dams to varying degrees. The growth in farm dams during the streamflow record period is not known. However, the growth in farm dams development since 1991 is known to be significant. To estimate the runoff from the catchment if the farm dams did not exist, the model was run, first with the farm dams volumes at 1991 levels and the second time without the farm dams. The difference in runoff values obtained from the two model runs is the estimated volume trapped in the farm dams. This volume was then added to the measured runoff data for the period 1975 to 1988 to produce the "annual adjusted runoff".

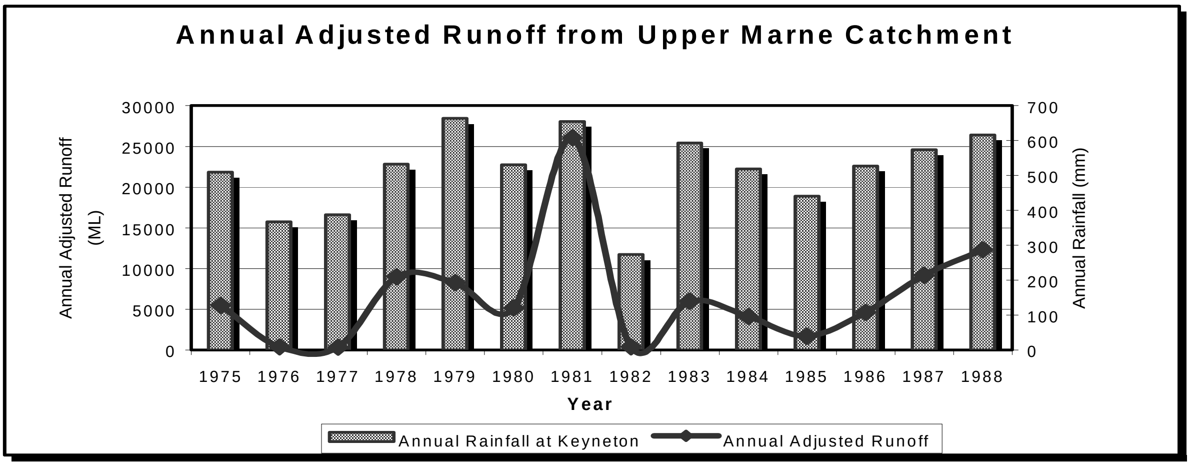


Figure 11. Annual Adjusted Runoff From Upper Marne Catchment

Figure 11 illustrates the high dependency of the runoff from the catchment with rainfall. It is also illustrated that during the dry years of 1976, 1977 and 1982 when the annual rainfall was less than 400 mm, the catchment does not generate any significant runoff. The mean and median annual adjusted runoffs from the Upper Marne Catchment for the period 1975 to 1988 are 6644 ML and 5340 ML. This

represents a 10% and 13% reduction in the mean and median runoff from the Upper Marne catchment at the 1991 levels of farm dam development.
To further characterise the sub-catchments within the Upper Marne catchment, runoffs from the individual sub-catchments were computed. The measured runoff was proportionally allocated to each of the sub-catchments based on the flow distribution provided by the model. Annual adjusted runoff from the sub-catchments of Western Slopes, Springton, Eden Valley, Marne, Keyneton and Somme was calculated by adding the water trapped in storage from the smaller catchments within. For example runoff from the Western Slopes sub-catchment was the summation of runoffs from the sub-catchments of WS1, WS2, WS3 and WS4 (Figure 2). The annual adjusted runoff from the six sub-catchments and the corresponding current (1999 levels of development) farm dam densities are shown in Table 5 and Figure 12.

Table 5: Sub-Catchment Characteristics.

No.	Sub-Catchment	Area (Sq. Km)	Dam Volume (ML)	Dam Density (ML / Sq.Km)	Mean Annual Adjusted Runoff (ML) (1975 – 88)	Median Annual Adjusted Runoff (ML) (1975 – 88)
1	**Western Slopes**	14.8	723	48.8	954	918
2	**Springton**	32.5	390	12.0	2837	2739
3	**Eden Valley**	31.6	682	21.6	918	600
4	**Marne**	38.4	158	4.1	597	369
5	**Keyneton**	48.9	263	5.3	800	500
6	**Somme**	75.7	116	1.5	543	314

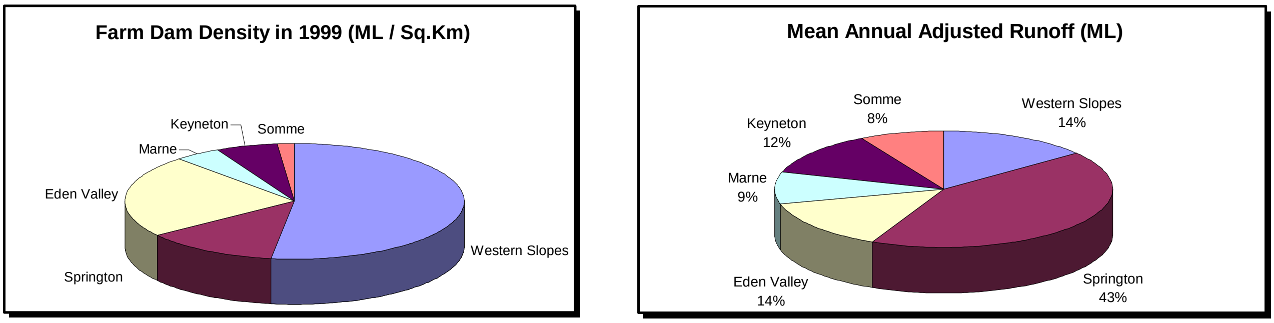


Figure 12: Farm Dam Density and Annual Adjusted Runoff from Sub-Catchments.

It can be seen from Table 5 and Figure 12 that:

- Western Slopes, though being the smallest sub-catchment, has the highest farm dam density and generates more runoff than the other sub-catchments except for Springton.

- Springton generates the highest runoff and has a low farm dam density compared to the other higher rainfall areas of Western Slopes and Eden Valley.

- Eden Valley has the second highest farm dam density and generates only 12% of the annual adjusted runoff from the whole catchment.

- Marne, Keyneton and Somme sub-catchments contribute to a very low percentage of the annual adjusted runoff from the whole catchment and also have low farm dam densities. These sub-catchments are in the lower rainfall area compared to the other three sub-catchments.

To understand the extent of development within these sub-catchments, the existing farm dam developments in each of these catchments is compared to the allowable limit* of development as shown in Table 6.

Table 6: Allowable Farm Dam Development.

No	Sub-Catchment	Allowable* Farm Dam Development (ML)	Existing Farm Dam development (ML)	Comments
1	Western Slopes	440	723	Above Limit
2	Springton	1487	390	Below Limit
3	Eden Valley	252	682	Above Limit
4	Marne	184	158	Below Limit
5	Keyneton	234	263	Above Limit
6	Somme	136	116	Below Limit

***** The sustainability indicator (State Water Plan, 2000) as currently under operation in the Mount Lofty Ranges watershed requires that farm dam development does not exceed 50% of the median annual adjusted runoff from the catchment.

Based on this indicator, the possible management scenarios in the sub-catchments of the Upper Marne catchment are:

- Current farm dam developments in wetter areas of Western Slopes, Eden Valley and Keyneton have already exceeded the allowable limit of development and will require some form of immediate control on further development.

- Farm dam developments in the drier areas of Marne and Somme have not reached their allowable limits. While the current development in these sub-catchments is less than their allowable limit by only a few megalitres, due to lower rainfall in these sub-catchments they are likely to develop less rapidly than the others. For this reason, control on further developments in these two catchments is less critical than in the other sub-catchments.

- The only sub-catchment that is not fully developed is the Springton sub-catchment. As shown in Table 5 this is the sub-catchment that contributes the most (45%) of the runoff generated from the Upper Marne catchment. There are still a few sub-catchments within the Springton sub-catchment that do not have large on-stream “controlling dams”. Further farm dam development in these "free-to-flow" sub-catchments is far more likely than in the Marne and Somme catchments. Hence, further development in Springton sub-catchment will not only lead to further reduction in flows leaving this sub-catchment but also reduce the streamflow leaving the Upper Marne catchment as a whole. This will have a direct impact on the crucial downstream water requirements such as:

- streamflow required for groundwater recharge downstream of Cambrai, between Cambrai and Black Hill,
- streamflow required for the survival of the downstream eco-systems including the area downstream of Black Hill.

Hence, the need for controls on further farm dam development in the Springton sub-catchment is more crucial and urgent in comparison to the need for controls in the Marne and Somme sub-catchments. In addition, given the over development of the Western Slopes and Eden Valley sub-catchments, consideration should be given to not permit further development in the Springton sub-catchment.

Current Scenario - Runoff with farm dam volumes raised to 1999 levels

Adopting the earlier calibration, the spatial layout and farm dam volumes from the 1999 survey were included in the model. The model was run and the results were analysed for different time scales, viz., annual, monthly and daily flows and the impact on annual adjusted runoff was calculated.

<u>Annual Flows</u>

Based on the estimates from modeling, the farm dams at 1999 levels of development intercept an average of 1200 ML/year of the flow generated in the upper catchment. For the period 1975 to 1988, this represents 18% of the mean and 24% of the median annual adjusted flows generated. This percentage reduction of annual runoff varies in individual years, and as shown in Figure 13, the impact is marginal during a wetter year (such as 1981) and very high during a drier year (such as 1982), though the runoff during dry years is also very low. The impact is greater in years following a dry year (as farm dams will be empty by the end of a dry year), whereas there might be carryover in other years.

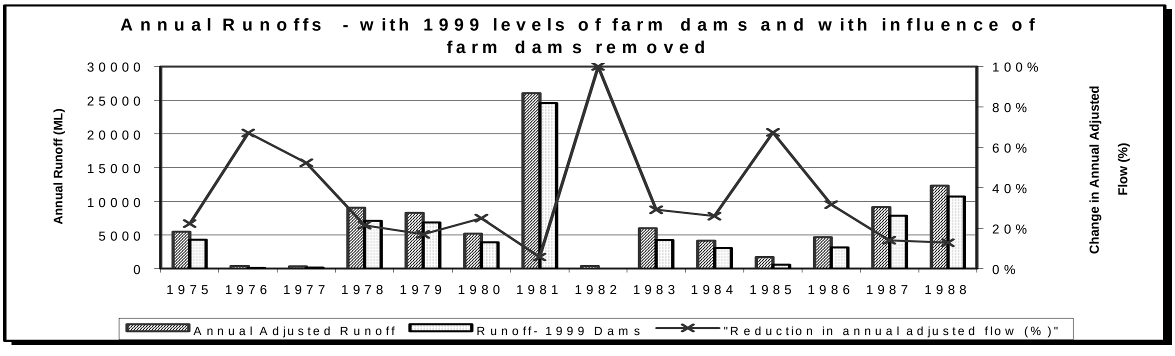


Figure 13. Change in Annual Runoff Due to Farm Dams as at 1999

Monthly Flows

The comparison of the median monthly values of annual adjusted and current flows (Figure 14) indicate that the impact of farm dams is greatest during early winter when the rains start (June/July). This is due to the farm dams being relatively empty following the summer months and the runoff generated by the initial rains being trapped by the dams. The impact of the dams is less significant during the next few months (August and September) as the dams are progressively filled-up and more catchments are free to flow. Drier years may not show the same pattern as described in Figure 14. Where runoff is insufficient to fill the dams, their impact may continue at higher levels across the entire winter period.

Though the percentage change in flow (between pre-development and current scenarios) during the drier months are shown as exceeding 80% the true impact is not highly significant as flows are historically low during these months. However, this reduction in flows during the drier months could be of importance with respect to environmental flow requirements.

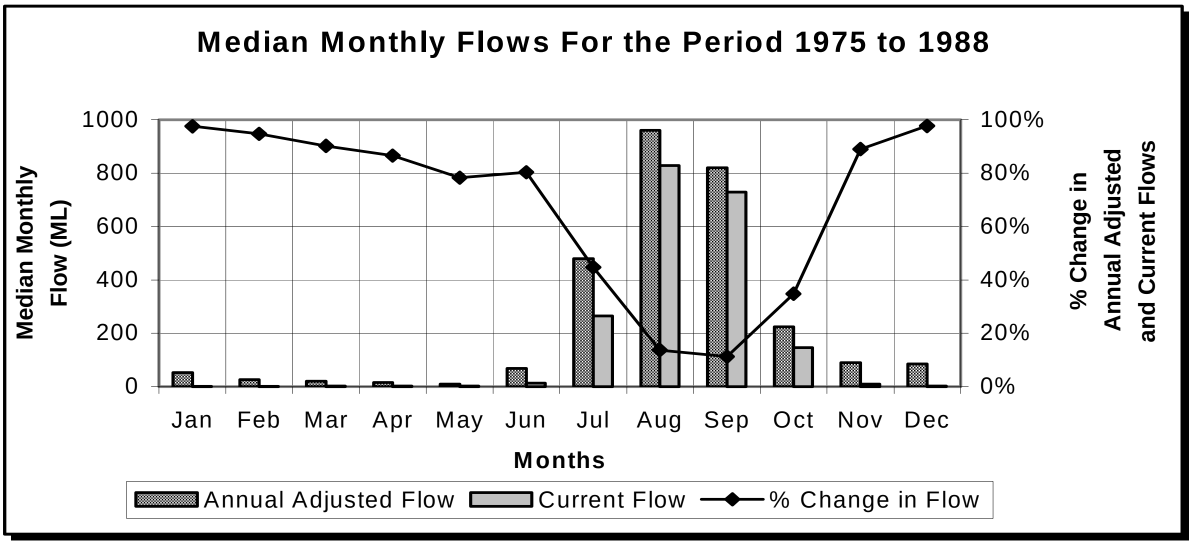


Figure 14. Median Monthly Flows

Daily Flows

Frequencies of daily flow exceedance for different flow ranges for pre-development and current scenarios are shown in Table 7 and plotted in Figure 15. Table 7 also shows the reduction in the number of significant flow days. For example, a flow of 1.0 ML/day or higher would have occurred for 93 more days in an average year prior to dam construction. This difference diminishes as the flow increases.

Table 7: Flow Exceedance Values of Pre-development and Current Scenarios

Flow (ML/day)	**Pre-Development Scenario** – No. of days of flow exceedance	**Current Scenario** – No. of days of flow exceedance	Difference in flow exceedance days
0.1	321	153	168
1.0	206	113	93
5.0	98	80	18
10	71	63	8
50	27	24	3
100	15	14	1

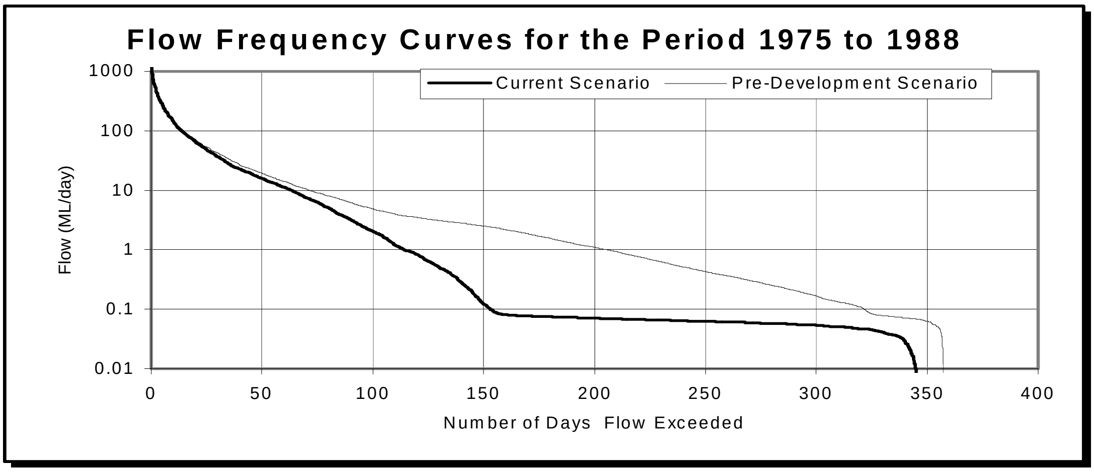


Figure 15. Flow Frequency Curves Comparison

The comparison of daily flows under pre-development and current scenarios indicates a significant reduction in the duration of mid flows due to construction of farm dams. However, high flows (> 10 ML/day) have largely been unaffected. This suggests that flows of size large enough to reach the River Murray have not been greatly impacted, and possibly it is the sequence of low rainfall years that has had a dominant influence on these high flows.

The change of mid flow events are more likely to affect the total volume of recharge occurring downstream of the gauging station and the survival of the streamflow dependent ecosystems further downstream. To ensure that these highly important mid flow events are maintained it is crucial to control further development of farm dams in the "free-to-flow" catchments in the wetter areas, particularly in Springton, as flows from these sub-catchments contribute to a major proportion of the flow generated from the catchment.

Future Scenario: Runoff with further farm dam development

Scenario 3 is a possible development level in the year 2009 if development controls were not put in place. It assumes an increase in farm dam development equal to the previous 10 years.

The rate of increase of farm dam volumes between 1991 and 1999 was calculated for each sub-catchment. This rate was then applied to the 1999 farm dam volumes to obtain the projected farm dam volumes in the year 2009. The model was then run with these projected farm dam volumes and the results were then compared to the flows estimated with the 1991 and 1999 farm dam volumes (Table 9).

Table 8. Projected Dam Volumes

Sub-Catchment	1999 Dam Volume (ML)	Projected Dam Volume (ML)
Western Slopes	723	2024
Springton	431	820
Eden Valley	689	1449
Marne	158	395
Keyneton	314	596
Somme	117	164
Total	2433	5448

Table 9. Reduction in Median Annual Runoff Due to Different Levels of Farm Dam Development

Farm Dam Development Scenarios	Median Annual Runoff (ML)	Reduction in median annual flows due to dams (%)	Average streamflow trapped in farm dams (ML)
Pre-Development Scenario: No dams	5340	0%	0
Past Scenario: 1991 level of farm dam development.	4638	13%	660
Current Scenario: 1999 level of farm dam development.	4075	24%	1175
Future Scenario: In 2009 if farm dam development continued at current rate.	3075	39%	1940

The 2009 scenario, as indicated in table 9, suggests that farm dams would intercept on an average 1940 ML/year of the flow generated from the upper catchment. This represents a further reduction of 10% in the mean and 15% reduction in the median of the current runoff at Cambrai.

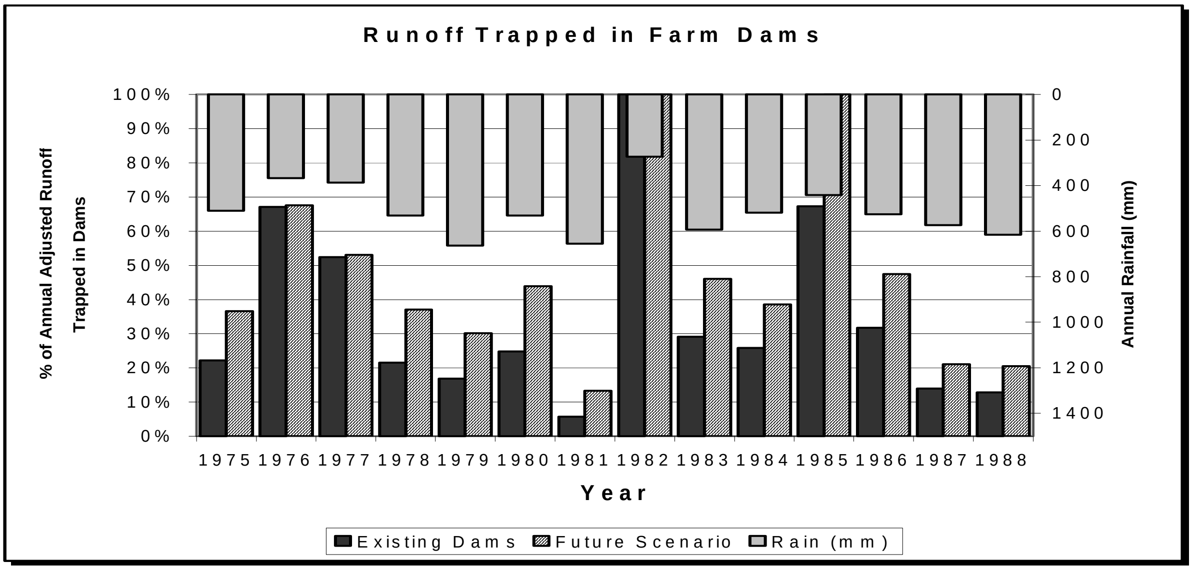


Figure 16. Comparison of Current and Future Runoff Trapped in Farm Dams

Further development of farm dams would mainly have impact on low and medium rainfall years, such as 1976, 1982 and 1985 (Figure 16), and based on the runoff estimated by the model there would be no streamflow downstream of the gauging station during some of those years. This would have direct consequences on the total volume of groundwater recharge downstream of the gauging station and also on the survival of the streamflow dependent ecosystems further downstream.

During wetter years, such as 1981, the additional volume intercepted by the dams would be marginal compared to the runoff, and hence the increase in percentage reduction of runoff would also be minimal.

This scenario possibly represents the best result if no development controls were placed. Given the current level of demand, the rate of increase may be significantly higher than in the past and it is more likely that the areas of the catchment which are still free-to-flow, as in the Springton sub-catchments, will be dammed.

CONCLUSIONS

1. *Representivity of Data*

The rainfall data (1973 to 1997) used for this study provides a good temporal distribution, as it includes a few near average rainfall years (1975, 1980), a few good wet years (1992, 1996) and a few good dry years (1982, 1994). The data set also provides for a reasonable representation of the spatial distribution of rainfall stations within the catchment. These two factors provide a good representative basis for usage of the data for further rainfall-runoff modelling process.

The annual runoff values recorded between 1973 and 1997 for the Upper Marne catchment indicate a high degree of variability, with the mean and median annual runoffs being 7,710 ML and 4,774 ML respectively. The rainfall-runoff relationship also indicates a high degree of dependency of runoff on rainfall, and hence, consistency in the rainfall-runoff relationship. These two factors of high variability in runoff data and consistency in the rainfall-runoff relationship indicate a good representation of the streamflow data for further modelling purposes.

However, it has to be noted that, in comparison to the 115 years of rainfall data available at Keyneton the 15-year data set used for this study represents a drier than average rainfall period. Furthermore, rainfall data from four of the six stations used for this study are privately operated and the data from them needs further verification.

2. *Calibration of Rainfall-Runoff Model*

A rainfall-runoff model was used to calibrate runoff from the available data and estimate runoff from the long-term rainfall data. The model provided a good calibration for annual and monthly data. The model also provided good results for an average rainfall year but tended to underestimate the runoff volume during wet years. Estimation of base flows and low flows during the end of runoff events was limited by data availability. To address the issue of measurement of low flows the stream gauging station at Cambrai was recently redesigned and upgraded.

Due to limitations in available streamflow data calibration of the model in this study was carried out with runoff data from only one gauging station. Calibration, in general, can be improved with runoff data from more than one stream gauging station if the catchment does not have uniform characteristics viz., rainfall, soil type, land use pattern etc. This could be achieved, to start with, by gauging the streams from the major sub-catchments that are in different rainfall zones. Further improvement in calibration can be achieved with input of more information on varying soil types, land use conditions and data on actual water usage from farm dams.

Since the Marne catchment is made up of two major tributaries, the Marne and Somme, that are of very different conditions, consideration is currently being given to gauge them individually.

3. *Scenario Modelling*

The rainfall-runoff model constructed and calibrated for the Upper Marne catchment was run for 3 different case scenarios to study the impact of different levels of farm dam development on the streamflow measured at Cambrai for the period 1975 to 1988. Water usage rate was assumed to be 30% in all the three scenarios. This rate allows for some carryover of storage for following years, and considering the lack of water usage information, is assumed to be the most appropriate usage rate. It should anyhow be recognised that greater usage rates will impact more heavily on streamflow. The results of the three case scenarios are:

i. **Pre-Development Scenario:** The model was run with the impact of farm dams removed, and the results indicate that the 1991 levels of farm dam development would have reduced the mean and median annual runoff by 10% and 13% for the period 1975 to 1988.

ii. **Current Scenario:** The model was run with the 1999 levels of farm dam development and the results indicate that:

- The farm dams, at 1999 levels of development intercept on average 1200 ML/year of runoff generated from the Upper Marne catchment. This represents a reduction of 18% and 24% of the mean and median annual runoff generated from the pre-development scenario.
- This percentage reduction in annual runoff varies in individual years, the impact being marginal during a wetter year (such as 1981) and very high during a drier year (such as 1982).
- The farm dams have a significant impact on the runoff during early winter, and a major proportion of the runoff generated by the early rains are trapped in the dams. A similar impact is felt during late winter and early summer when pumping from the dams for irrigation starts.
- Though the reduction in runoff due to farm dams is quite high during summer months, the true impact is not highly significant during this period. This is because flows are historically low during the summer period, but it is recognised that summer flows could play a crucial role in the survival of streamflow dependent ecosystems.
- The major effect of farm dams is reduction in the flow duration of the low and mid flow events. This would directly affect the volume of groundwater recharge in the immediate downstream area, between Cambrai and Kongolia and the survival of the streamflow dependent ecosystems further downstream. High flows have largely been unaffected by farm development, suggesting that flows of size large enough to reach the River Murray are possibly more influenced by a sequence of low rainfall years.

iii. **Future Scenario:** This scenario was modelled for a possible development level in the year 2009 if development controls were not put in place. It assumes an increase in farm dam development equal to the previous 10 years. The results of this case indicate that:

- The farm dams, at 2009, assuming level of development equal to the last 10 years, intercept on an average 1940 ML/year of runoff generated from the Upper Marne catchment. This represents a reduction of 28% and 39% of the mean and median annual runoff generated from the pre-development scenario.

- In extreme cases of dry years such as 1982, which was a very low rainfall year, there would be no flow passing the gauging station in future if farm development continued at the same rate.

4. *Technical Conclusions*

Rainfall data used in the study relied on records from 2 official stations and 4 unofficial gauges. To obtain a good rainfall distribution for the catchment, data collection at these 4 unofficial sites should be continued and also formalised. Furthermore, to gain better knowledge and information on the change in rainfall with altitude, collection of rainfall data is recommended at a high altitude site north of Eden Valley.

Continuous streamflow records are available only for the period 1975 to 1988. Hence data for this period alone was used for modelling purposes. Stream gauging should be continued at Cambrai, with the station being upgraded to enable measurement of low flows. The Department for Water Resources has recently redesigned and upgraded the station for this purpose. Additional stream gauging should be considered at least at two more sites. The first should be located at a site upstream of the confluence of the Marne and Somme rivers to delineate the flows from the two catchments. The second should be located in the downstream portion of the catchment, to monitor the runoff reaching the wetlands and the mouth of the catchment.

The Department for Water Resources is currently undertaking a review of the hydrological monitoring network in the state. Consultations are currently being held as part of this review with the River Murray Catchment Water Management Board to consider further monitoring of rainfall and runoff.

The method for estimation for farm dam volumes used for this study is currently being reviewed by the department, which would provide better estimates of the farm dam volumes for future analysis. Further information on water usage from farm dams would also provide better input for future analysis of impact of farm dams on streamflow.

5. *Management Conculsions*

The combined farm dam capacity in the upper Marne catchment has more than doubled in the last decade. Based on 1999 data, there are 640 farm dams in the upper Marne catchment, with a total estimated storage capacity of 2,400 ML.

In the wetter sub-catchments of Western Slopes, Keyneton and Eden Valley the current levels of farm dam development have exceeded the allowable limit of development adopted in the Mount Lofty Ranges Catchments. Some form of control on development in these sub-catchments would be consistent with measures adopted in adjacent areas.

In the drier sub-catchments of Marne and Somme current developments are below the allowable limit by only a few megalitres. Control on further development in these sub-catchments could be of less priority as they are likely to develop less rapidly than the other sub-catchments.

The only sub-catchment that is not near or exceeding full development at this stage is the Springton sub-catchment, which also generates almost fifty percent of the runoff generated from the entire Upper Marne catchment. Further development in this sub-catchment would impact the runoff leaving the Upper Marne catchment which, in turn, would affect the volume of groundwater recharge and the survival of streamflow dependant ecosystems downstream of Cambrai. Control on further farm dam development in the Springton sub-catchment would preserve a significant proportion of the natural flow regime for the catchment, protecting groundwater recharge and ecosytem water needs.

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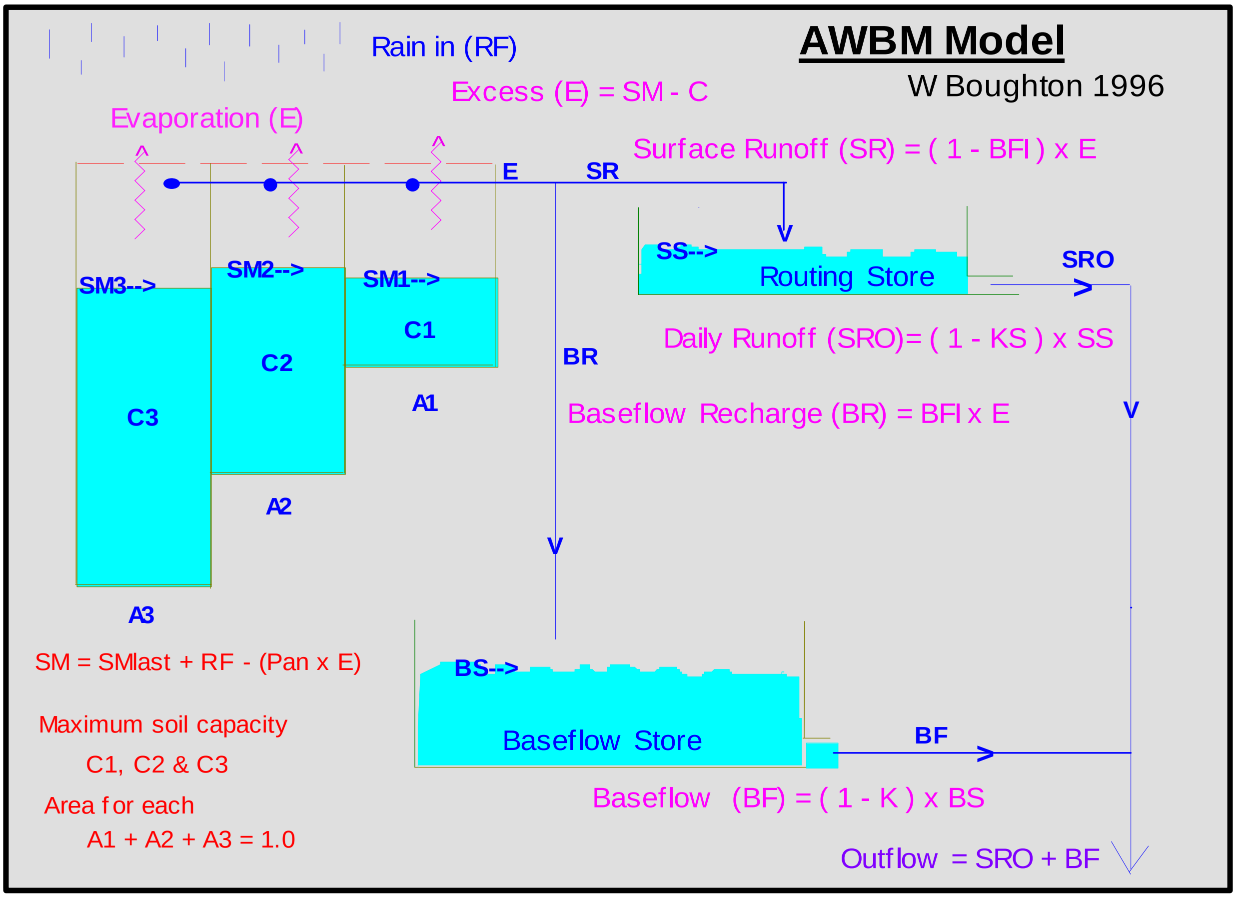
APPENDIX A. AWBM - Model Description

The AWBM model uses three surface stores to simulate partial areas of runoff. The water balance of each store is calculated independently on a daily time step. At each day, the rainfall is added to each of the soil moisture stores and evapo-transpiration is removed from each store. Runoff occurs if any of these stores exceeds their capacity.

The size of the stores is allocated to stimulate the catchments' non-linear response to rainfall as its wetness increases. The layout of the structure diagram of the model is shown in the figure below.



The basic input data required by the model are daily rainfall and runoff records, monthly evaporation data, catchment areas and farm dam details. The model is then calibrated against the measured daily runoff records. To calibrate the rainfall-runoff model 9 parameters are required. Calibration requires adjustment of these parameters to obtain flows that are as close as possible to the measure flows.

The results of calibration can be visually assessed by plotting the measured and modeled flows on daily, monthly or yearly time steps. Further assessment by statistical analysis can be carried out for monthly and yearly data by comparing the means, the correlation coefficients (R squared), standard deviations, coefficient of variations and coefficient of skewness of the modeled and measured flows.

APPENDIX B. Upper Marne Catchment - Farm Dams Information

NO.	Catchment	SUB-CAT	Sub_Cat Area (Km2)	Dam Area (Km2)	Dam Volume (ML)
1	Eden Valley	EV-1 Total	0.734	0.011509	13.695
2	Eden Valley	EV-2 Total	2.164	0.025848	28.532
3	Eden Valley	EV-3 Total	5.051	0.026208	23.652
4	Eden Valley	EV-4 Total	0.619	0.016162	24.523
5	Eden Valley	EV-5 Total	3.029	0.064569	154.73
6	Eden Valley	EV-6 Total	2.082	0.038399	54.146
7	Eden Valley	EV-7 Total	0.303	0.011842	14.943
8	Eden Valley	EV-8 Total	3.635	0.084962	183.79
9	Eden Valley	EV-9 Total	4.968	0.028351	27.526
10	Eden Valley	EV-10 Total	0.937	0.018225	25.409
11	Eden Valley	EV-11 Total	6.572	0.031119	29.695
12	Eden Valley	EV-12 Total	1.559	0.050889	108.719
	Eden Valley Total		**31.653**	**0.408083**	**689.36**
13	Keyneton	K-10 Total	5.867	0.03428	56.206
14	Keyneton	K-11 Total	2.7	0.00712	5.822
15	Keyneton	K-12 Total	1.229	0.009183	7.722
16	Keyneton	K-13 Total	1.244	0.00633	4.637
17	Keyneton	K-14 Total	9.369	0.038522	30.779
18	Keyneton	K-15 Total	5.773	0.040522	46.582
19	Keyneton	K-1 Total	0.812	0.012108	20.545
20	Keyneton	K-2 Total	1.771	0.019859	22.59
21	Keyneton	K-3 Total	1.408	0.004546	4.402
22	Keyneton	K-4 Total	0.483	0.007934	7.269
23	Keyneton	K-5 Total	4.468	0.011806	11.415
24	Keyneton	K-6 Total	0.631	0.006765	6.88
25	Keyneton	K-7 Total	5.803	0.02438	20.922
26	Keyneton	K-8 Total	2.894	0.008851	8.149
27	Keyneton	K-9 Total	1.053	0.025812	43.549
	Keyneton Total		**45.505**	**0.258018**	**297.469**
28	Marne	M-1 Total	12.681	0.049247	61.289
29	Marne	M-2 Total	9.023	0.033362	39.683
30	Marne	M-3 Total	16.692	0.05319	56.776
	Marne Total		**38.396**	**0.135799**	**157.748**
31	Somme	S-1 Total	6.522	0.023875	31.72
32	Somme	S-2 Total	11.502	0.055621	47.054
33	Somme	S-3 Total	2.966	0.007666	7.707
34	Somme	S-4 Total	8.39	0.000207	0.077
35	Somme	S-5 Total	10.562	0.01481	11.884
36	Somme	S-6 Total	5.01	0.010493	7.271
37	Somme	S-7 Total	16.004	0.013152	11.254
38	Somme	S-8 Total	14.727	0	0
	Somme Total		**75.683**	**0.125824**	**116.967**
39	Springton	SP-1 Total	1.386	0.031637	41.406
40	Springton	SP-2 Total	0.48	0.186271	42.529
41	Springton	SP-3 Total	8.123	0.102306	116.748
42	Springton	SP-4 Total	2.529	0.030791	49.228
43	Springton	SP-5 Total	1.743	0.027298	52.356
44	Springton	SP-6 Total	3.387	0.024858	29.106
45	Springton	SP-7 Total	5.52	0.05664	75.453
46	Springton	SP-8 Total	4.163	0.019187	18.996
47	Springton	SP-9 Total	5.171	0.008008	5.66
	Springton Total		**32.502**	**0.486996**	**431.482**
48	W.Slopes	WS-1 Total	2.641	0.05059	147.791
49	W.Slopes	WS-2 Total	5.184	0.172934	531.776
50	W.Slopes	WS-3 Total	1.673	0.01419	16.022
51	W.Slopes	WS-4 Total	5.332	0.022279	27.519
	W.Slopes Total		**14.83**	**0.259993**	**723.108**
	Grand Total		**238.569**	**1.6747**	**2416.1**