Impacts and Implications of Farm Dams on Catchment Hydrology: Methods and Application to Chaffey Catchment

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Abstract In the last twenty five years, numbers of farm dams have increased significantly in response to changing land use and land management strategies. However, the construction of large numbers of dams in a catchment impacts on water resources in a number of ways, in particular, by reducing streamflow. Consequently, other uses of water downstream of dams, including environmental, may be compromised. Because the impacts of farm dams on the hydrologic regime have widespread environmental and socio-economic ramifications, future development needs to be assessed in legislation and policies supported by sound scientific monitoring and analysis. Examination of the legal/policy context indicates that it does not specifically address the environmental impacts of farm development, nor are there measures in place to establish, monitor and control relevant water allocations. A project funded principally by the Murray Darling Basin Commission aims to study 25 catchments within the Murray Darling Basin which have experienced significant dam development. Modelling the water balance in the catchments involves a 'before and after' approach to dam development to assess the downstream impacts of farm dams, especially on low flows across a range of climatologies and landscapes. The description and analysis of results from an initial catchment defines part of the methodology for this project and provides some indicative results.

1. INTRODUCTION

Farm dams are an ubiquitous feature of the Australian rural landscape, providing essential water supplies for domestic, stock and irrigation use. Farmers generally rely on these dams for seasonal 'drought insurance' in areas with highly variable rainfall. Furthermore, they often represent a component in erosion mitigation works. Since the early 1970's, the numbers of farm dams have increased significantly in response to changing land use and land management strategies. The development of these dams is controlled by a raft of State and Local legislation and is supported by a range of policies including tax incentives and soil conservation programs. However, the construction of large numbers of farm dams in a catchment impacts on water resources in a number of ways, in particular by reducing streamflow (Banens, 1981; Ockenden and Kotwicki, 1982; Cresswell, 1992). These impacts have widespread environmental and economic ramifications. Consequently, future development needs to be assessed within a legislative and policy context supported by sound scientific monitoring and analysis.

The current study models the dynamic water balance in the Chaffey Storage catchment of the Namoi Basin, New South Wales, to assess downstream impacts of farm dams. The description and analysis of results from this study define part of the methodology and provide some indicative results. Complex landuse and land management strategies within the catchment emphasise the difficulty in isolating farm dam development from other catchment changes.

2. CURRENT POLICY/LEGISLATIVE STRUCTURE

The present legislative and policy structure for farm dams is a multi-tiered system comprising incentives and constraints on dam development at National, State, local and catchment levels. The provisions are complex and difficult to administer because:

- in each State, a number of Acts and policies deal with farm dams;
- the granting of permits and licences may be handled by several authorities, including State agencies and Local Government;
- the statutory criteria upon which dam applications are to be assessed are non-existent or unclear; and
- the adoption and administration of specific Local Government regulations (such as Local Government Plans in New South Wales) by councils varies in response to available resources and expertise, as well as local conditions and expectations.

Recent initiatives for water reform in Australia have been instigated through the COAG strategic framework for water resource policy (Council of Australian Governments, 1994) and the Murray Darling Basin Commission Water Audit. These documents, and the policies drawing from them, acknowledge the need to balance consumptive water use and river health through integrated approaches to ecological sustainability and catchment management practices. In response, the States and Territories are developing new strategies for water resources management. These include an interim cap on consumptive water use and the development of flow management strategies for the benefit of the environment. It is also hoped that a move towards a 'water market' will ultimately increase water use efficiency. Farm dams are an issue in these strategies because of their role in:

- diverting and redirecting water before it enters the stream, and is therefore open to formal allocation; and
- supporting farming, which competes with other uses (including the environment) for access to a limited resource.

Running counter to this criticism are arguments that support the expansion of farm dam use because of their value in protecting against losses during seasonal droughts, and as sediment traps in gully erosion networks. These competing assessments of the impact and value of farm dams have created a number of conflicting administrative and legislative constraints and incentives. At the national level, government policy supports farm dam development through tax incentives and drought investment allowances. Furthermore, the construction of a farm dam attracts a three year tax rebate when it can be demonstrated that the work is part of a Landcare project. At a regional and catchment scale, policies that impinge on farm dam development are concerned generally with allocation issues.

These issues have come to the fore in recent times because of the MDBC's cap on consumptive water use. During off-allocation periods, when unregulated flows are sufficient to supply irrigation demand and, at the same time meet downstream requirements, all or part of the water used by irrigators is not counted against irrigator's allocations. Consequently, farmers take advantage of these periods to fill their storages. The impact of this policy is to increase water availability for diversion during the rest of the year. In streams with significant on-farm storage capacity, the diversion and use of off-allocation water can have significant effects on the natural hydrological regime of rivers. These impacts are linked to conditions which make on-farm storage construction economic, such as commodity prices and financial incentives.

Thus, the present scheme has a cumbersome administrative system which supports over-regulation and has the potential to over-commit resources. Furthermore, the current structure is based on an antagonistic system of constraints and incentives which reflect a mismatch between policies for dam construction and those relating to water for the environment. Policy development needs to address this mismatch to optimise policy alignment and disable the current antagonistic system, and requires the support of sound scientific monitoring and analysis.

3. CATCHMENT DESCRIPTION

The Chaffey catchment is within the Namoi Basin in northern New South Wales and is located south of the city of Tamworth (Figure 1). The catchment has a total area of 420 km ^{2} and incorporates the drainage area for the Peel River upstream of the Chaffey Dam. The topography comprises precipitous slopes and rough terrain along its southern boundary and eastern region with slopes >15°. A north-south trending fault escarpment bisects the catchment and separates this precipitous country from gently undulating terrain in the western section. The topography is defined by the underlying geology both in terms of lithology and structure.

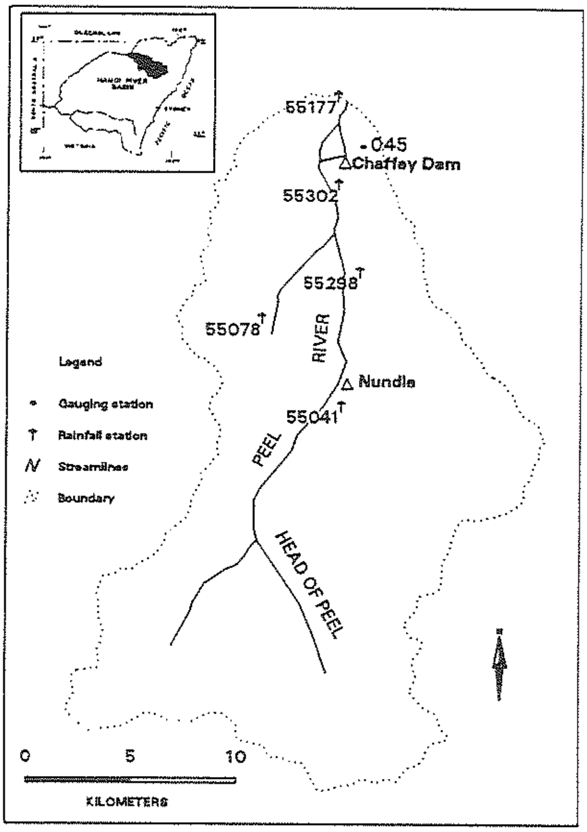

Figure 1: Location of the Chaffey catchment

The catchment has highly complex geology being located within the central zone of the New England Fold Belt which includes the Peel Thrust Fault. The stratigraphic sequence comprises:

Recent	alluvium, colluvium
Tertiary	Liverpool Range Volcanics (basalt, dolerite)
Permian	Back Creek Tonalite
Devonian	Tamworth Group (cherty argillite, arenite, breccia, limestone)
Ordovician	Woolomin Beds (greywacke, slate, phyllite, jasper)

The dominant soils are non-calcic brown soils which occur throughout the area, with chocolate prairie soils in the precipitous terrain associated with the volcanics, and red earths/red podzolics associated with the metasediments. Black prairie soils occur as alluvial valley fill. Soil erosion is problematic in the upper and western sections of the catchment, in association with soils developed on highly fractured and sheared sedimentary sequences of the Peel Thrust Fault.

The predominant landuse is grazing, with State forest in the precipitous terrain in the eastern and south-eastern sections of the catchment. Limited areas of cropping are associated with alluvial flats near the township of Nundle, which occupies a small urban area.

4. A CHRONOLOGY OF CATCHMENT CHANGES

Farm dams have been constructed within the Chaffey catchment to satisfy a number of requirements including:

- supply of domestic and stock water;
- erosion control; and
- water supply for fire control in the upper and eastern forested sections of the catchment.

Consequently, the development of farm dams has remained relatively static in some sections of the catchment, whilst in others, development has reflected changes in land management practices. At a catchment scale dam numbers have changed as shown in Table 1.

Table 1: Number of farm dams in Chaffey catchment evident from aerial photography

Year	Number of dams
1973	118 dams
1983	245 dams
1990	392 dams

Immediately after Chaffey Dam was constructed in 1979, the resumption of 10.15 km^2 in the western foreshore area was associated with rapid farm dam development to improve local water supply for stock. A significant proportion of the dams in this area was constructed between 1980 and 1985 using a one dam per paddock approach. However, since this area is one of the most erodible sites in the catchment, dams also represented important components in erosion control works. Further management strategies included the maintenance of 70% ground cover as native pasture with some Medic 173 sown for pasture improvement over an unspecified time.

Pasture management during this period had a significant impact on reducing runoff. The effectiveness of the dams as 'seasonal drought insurance' under these conditions was diminished and in the 1992 drought, serious stock losses occurred. Consequently, after the drought, farm dams were abandoned *in this part of the catchment* as the principal source of stock water supply, and the groundwater resource was developed. At present 50% of the western foreshore subcatchment is dependent on a trough water system, which is supplied by groundwater. This practice maximises water availability for stock by taking advantage of both the surface and groundwater resources.

In contrast to the management of the western foreshores subcatchment, the rest of the catchment has experienced less intensive pastoral development. Nonetheless, dam numbers have continued to increase in the upland sections of the catchment in response to pastoral activity and the construction of erosion mitigation works. Notably, in the 1990's, dams built in the upland section of the catchment are much larger structures.

No changes in dam numbers have occurred in the forested sections of the catchment near the catchment boundaries. However, broadscale logging of native forests and pine plantations in the upper eastern sections occurred immediately prior to 1973, with 15.1 km^2 clearfelled. Within this area an integrated system of forest roads, snig tracks and log landings is apparent.

Hydrologic responses to forest management practices include increases in baseflow and marked increases in peak flow response. Research in catchment yield responses to clearfelling or wildfire provide variable results but generally concur with modelling by Kuczera (1985). Where entire catchments or subcatchments contain a single forest age-class, the amount of streamflow delivered from that catchment will increase in the short term, and then decline in association with the water requirements of regrowth. As regrowth matures, the water yield of the catchment will gradually increase towards pre-fire levels.

For Ash-type forests, Kuczera showed that for every one per cent of mature forest converted to regrowth forest, a decline of 6 mm in annual water yield could be expected some 30 years later. Nandakumar and Mein (1993) estimated that, when 10 per cent of the catchment was cleared, there was a corresponding 33 mm increase in annual runoff, and that water yields peaked 2-3 years after clearing and then declined to pre-treatment levels after 5-8 years. In mixed species forest, water yields increased in the first year after clearing, with decreases occurring about two years after logging in response to abundant regeneration (Cornish, 1993). However, where the effective area of vegetation reduction was <20% of the total catchment area, no initial increase of catchment yield occurred.

5. METHODOLOGY

5.1 Catchment selection criteria

Catchments selected for detailed study for the project are located throughout the Murray Darling Basin within Victoria, the Australian Capital Territory and New South Wales. Generally the catchments are located in the western slopes of the Great Dividing Range. Landuse includes grazing, agriculture, rural residential and limited urban areas as small settlements/villages. Selection criteria of catchments are based on minimum data requirements including:

- 10 years of streamflow records
- 20 years of rainfall records
- *Fair to good* Australian Water Resources Council rating for streamflow data
- Aerial photography covering the total catchment for the period of streamflow record as a number of time slices (preferably >2)
- Evidence of substantial dam development.

The Chaffey catchment satisfies these criteria as follows:

- 19 years of streamflow records
- 14-101 years of rainfall records
- *Good* Australian Water Resources Council rating for streamflow
- Aerial photography for 1970, 1983 and 1990
- At a total catchment scale dam numbers have increased by more than three times in 20 years. However, farm dam densities and development rates vary considerably between subcatchments.

5.2 Quantification of farm dam development

Catchments which satisfy the selection criteria are initially analysed to determine the spatial and temporal variation of dam development during the period of streamflow records, with specific reference to the period since the late Sixties-early Seventies when dam development increased significantly. A number of aerial photographic runs for the catchment are interpreted to provide numbers and locations of dams together with other conservation structures such as contour banks. These data provide the basis for an initial assessment of a catchment, from which more detailed analyses can follow. These later analyses will include estimation of dam volumes and the area of catchments controlled by dams to provide explicit farm dam parameters (representing water losses) for the modelling.

5.3 Analysis of rainfall/runoff data

The discharge data were collected on a daily time step for gauging station 419045 (Figure 1), which was built in December, 1968. The median of rainfall data was obtained from five rainfall stations. Table 2 shows details of the rainfall stations used. Figure 2 shows the total volumes of rainfall and associated runoff events during 1968-1991. Notably, the summer and winter thresholds of rainfall amounts needed to yield an increase in stream discharge differ substantially, illustrating the special need in this catchment for any rainfall-runoff model to take antecedent conditions into account. The model in Ye *et al.* (1997) demonstrates the highly non-linear behaviour of responses that is needed in ephemeral catchments.

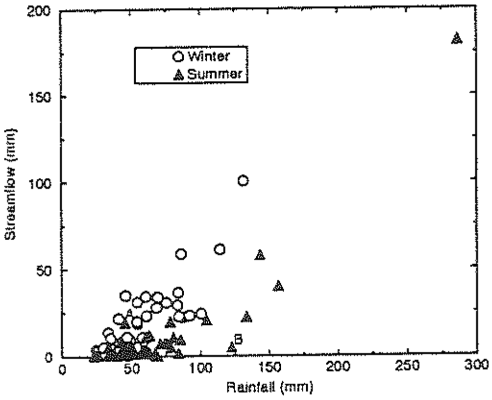

Figure 2: Runoff events during 1968-1991 at Chaffey catchment gauging station no. 419045

Table 2: Rainfall stations used in the water balance modelling

Station	Station no	Length of recording	Location
Nundle Post Office	55041	1890 - 1991	31.46S, 151.13E
Nundle (Benon)	55078	1953 - 1991	31.42S, 151.00E
Woolomin (Northcote)	55177	1958 - 1991	31.32S, 151.13E
Bowing Alley Point (Weona)	55298	1897 - 1991	31.40S, 151.14E
Nundle (Chaffey Dam)	55302	1977 - 1991	31.36S, 151.13E

6. WATER BALANCE MODELLING

The modelling process represents a 'first pass methodology' to extract the fundamental role of dams in the water balance. This approach involved a modified version of Jakeman *et al.'s* (1990) IHACRES model (Evans and Jakeman, 1997) to identify changes in the water balance during the study period.

The average relative parameter error (%ARPE), Bias B and Efficiency E are used to assess the performance of the model. These are given by:

$$ARPE = \frac{1}{N}\sum_{i=1}^{n}\frac{\hat{\sigma}_i^2}{\hat{a}_i^2} \qquad (1)$$

$$B = \frac{1}{N}\sum_{i=1}^{N}(Q_i - \hat{Q}_i) \qquad (2)$$

$$E = 1 - \sum(Q_i - \hat{Q}_i)^2 \Big/ \sum(Q_i - \overline{Q})^2 \qquad (3)$$

where each $\hat{\sigma}_i$ is the estimated error variance of model routing parameters; Q_i is the daily observed streamflow, $\hat{Q}_i$ is the daily modelled streamflow and $\overline{Q}$ is the mean value of the observed streamflow record, respectively.

The model performs best when both the bias and %ARPE are close to zero and the efficiency is close to one (Nash and Sutcliffe, 1970). Three-year subperiods were selected as calibration periods, starting and ending with low flows (in winter). Changes of bias during the study period were examined to indicate changes in catchment hydrologic behaviour.

7. RESULTS OF MODELLING

Table 3 shows the performance of the model calibrated on five separate time periods. Each model was then used in simulation mode on each of the other four periods and the Bias, B, and Relative Bias, $B/\overline{Q}$, was recorded (Table 4). The differently calibrated models are in general agreement about the change in streamflow which has occurred throughout the study period. The Relative Bias is another indicator of the reliability of the modelling in that it shows changes in flow (off-diagonal entries in Table 4) are typically much larger than model errors (diagonal bold entries). Figure 3 shows the model changes in average daily stream discharge $\Delta\hat{Q}$ from one period to the next. In Figure 3, the $\Delta\hat{Q}$ value at 1-2 on the abscissa denotes the bias for a given model applied on period 2 minus the bias for the same model applied on period 1. Similarly 2-3, 3-4, 4-5 denote changes occurring between the relevant periods. So, positive changes in $\Delta\hat{Q}$ indicate that there has been an increase in observed streamflow which is greater than the model expects, and vice-versa for negative changes.

Table 3: Model calibration performance

Model No. and Periods	Total runoff (mm)	Runoff %	Parameters of the model					Model performance		
			a	b	c	d	T.C	%ARPE	Bias (mm/day)	E
1 (22/06/71 - 19/09/74)	261.12	11.47	45	1	0.16	0.03	0.7	0.19	-0.01	0.814
2 (21/08/76 -20/08/79)	504.52	19.13	76	1	0.17	0.03	0.7	0.37	0.01	0.669
3 (01/06/83 - 30/05/86)	382.71	15.79	51	1	0.35	0.04	1.7	0.03	0.00	0.841
4 (06/03/87 -04/03/90)	351.56	15.4	41	1	0.37	0.05	1.6	0.05	0.00	0.754
5 (01/03/90 -31/12/91)	393.43	24.90	90	1	0.15	0.01	1.2	0.12	0.05	0.777

* a, b, c, d are parameters of the loss module of IHACRES while T.C. is the time constant of the linear module (see Evans and Jakeman, 1997)

Table 4: Simulation of calibrated models on other periods

Periods	Bias and Relative Bias ($B/\overline{Q}$)									
	Mol1		Mol2		Mol3		Mol4		Mol5	
22/06/1971 - 19/09/1974	**-0.01**	**-0.05**	-0.06	-0.24	0.03	0.11	0.03	0.14	0.02	0.07
21/08/1976 -20/08/1979	0.07	0.15	**0.01**	**0.08**	0.11	0.25	0.14	0.30	0.06	0.12
01/06/1983 - 30/05/1986	-0.07	-0.20	-0.12	-0.35	**0.00**	**0.00**	0.01	0.03	0.01	0.04
06/03/1987 -04/03/1990	-0.01	-0.04	-0.08	-0.26	-0.02	-0.05	**0.00**	**0.00**	-0.07	-0.22
01/03/1990 -31/12/1991	0.01	0.02	-0.06	-0.09	0.09	0.15	0.10	0.17	**0.03**	**0.05**

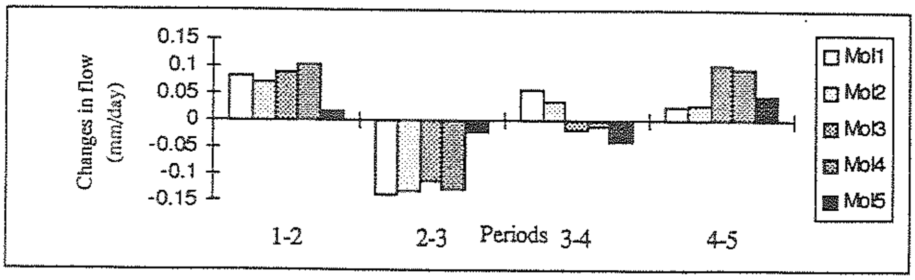

Figure 3: Model changes in discharge between adjacent period

8. DISCUSSION

The modelling results are consistent with expected streamflow volume responses to changes in Chaffey catchment during the 1970's to 1990's. In the 1970's, the water yield, according to the model, increased significantly. This could partly be in response to logging operations in the eastern uplands. The average amount of change from period 1 to period 2, 7.44 mm/year per percentage of catchment cleared, is less than that predicted by Nandakumar and Mein (1993) for Ash-type forests (11.88mm/year per percentage of catchment cleared). In the early 1980's a number of changes within the catchment can be associated with the model's estimated decreases in water yield:

- dam development increased in the early 1980's, in response to the drought of 1982/83 and there was reclamation of the western foreshores section of the catchment after the opening of Chaffey Dam with associated increases in dam numbers and land cover density;
- regrowth occurred in the forested area in the eastern uplands.

According to the model, the yield increased from 1987 onwards, as a number of management strategies were exercised in different parts of the catchment. The groundwater resource was developed in preference to dams in the western foreshore area and water usage by regrowth in forest management areas should have decreased towards pre-treatment levels.

9. CONCLUSIONS

In the Chaffey catchment landuse and land management are complex. Farm dam development varies spatially and temporally, and is concurrent with other management strategies including pasture and stocking manipulation, development of the groundwater resource, erosion mitigation works and forest management practices. This level of complexity emphasises the difficulties in isolating dam impacts from a raft of landuse/ land management changes with implications for research and policy development. However, it is encouraging that the model produces the type of results expected in terms of estimating the associated changes in water balance. Future research into farm dam impacts on catchment hydrology will investigate more extensively and intensively the relative significance of a number of variables affecting streamflow response.

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