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THE CANBERRA LAKE SCHEME - A REVIEW OF THE SILTATION PROBLEM

by

L. C. Noakes

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SUMMARY

The problem of siltation is inherent in the Canberra lakes scheme, currently under investigation by the Works Department, Canberra. Soil conservation officers have indicated that streams within the Molonglo catchment will carry a considerable load of silt in flood with consequent reduction of storage capacity in reservoirs; the present report carries the investigation a step further; it discusses siltation of proposed reservoirs and arrives at a preliminary estimate of likely siltation rates.

There are three principal methods of determining siltation rates - the application of empirical formulae, the measurement of actual silt load in streams and the comparison between catchments. The first method is too inaccurate for this investigation. The most reliable estimates are likely to come from a combination of the second and third methods. However estimates of siltation rates on the Molonglo can only be determined at present by the third method because no silt measurements have been carried out in streams within the catchment. Measurements should begin as soon as possible to provide an eventual check on present estimates of siltation rates.

The reliability of rates determined by the comparison of one catchment with another in which reservoir siltation has been measured, depends primarily on the similarity between the basic characteristics of the catchments concerned and, secondly, on the correctness of adjustments made to allow for differences in one or more of these basic characteristics - size, climate, stream characteristics and supply of silt. The trap efficiency of reservoirs must also be taken into account. Only size of catchment is amenable to mathematical adjustment; the adjustment of other factors is largely subjective and hence the method is not precise.

In the time available only two catchments, in which measurements of reservoir siltation were available, could be found with basic characteristics sufficiently close to those of the Molonglo catchment to provide useful comparison. These are the Werribee River catchment above the Melton River in Victoria and the catchment of Cunningham Creek above the old Railway weir near Harden, N.S.W. These catchments were examined in the field and compared with the Molonglo catchment.

A bracket of possible rates of siltation in the Molonglo is derived by refining the comparison of catchments in a number of ways; rates derived from the Werribee catchment are regarded as more reliable than those derived from Cunningham Creek. Estimates of annual siltation in acre feet and of the ½ and 2/5 life of the proposed Acton storage are given; the 2/5 life of the storage is possibly the critical point beyond which the ornamental and recreational functions of the lake become really impaired.

The results indicate that siltation in the proposed Acton storage is likely to be of the order of 50-100 acre feet per year; within that range, 60-70 acre feet per year or a 2/5 life of 50-60 years is suggested as a preliminary estimate. These estimates are based on present conditions within the catchment; variations in climate, land use or rabbit population will obviously affect siltation rates. The importance of rabbit control as a means of decreasing siltation is emphasised.

Although the Yarralumla reservoir promises longer life because of additional storage, it is very doubtful whether this applies to the critical area of the lake which lies in

the city, toward the head of storage. Possible differences in the pattern of siltation between the alternative reservoirs are discussed with the conclusion that as far as siltation is concerned, there is no present basis for preferring one reservoir to the other. However, investigation of differences in siltation between alternative storages should be attempted on the proposed model of the lakes scheme.

Preliminary estimates indicate that siltation will be a major problem in the lake scheme. Remedial measures lie primarily in the fields of soil conservation and land use but engineering methods of trapping silt may be important for immediate control. It is suggested that the dredging of sand deposits from deltas at the head of storage could serve the double purpose of assisting silt control and of providing much of Canberra's future supply of river sand to replace deposits to be submerged by the proposed lake.

INTRODUCTION

The Lakes Scheme on the Molonglo River, originally proposed by Burley Griffin in his plan for Canberra, has been the subject of a number of investigations in the past; none of these has been carried to a conclusion.

The newly appointed National Capital Development Commission has initiated a vigorous programme designed to collect sufficient data on the Lakes Scheme to review properly its efficacy and cost; investigations in the sphere of engineering are being carried out by the Department of Works, Canberra, with the co-operation of the Bureau of Mineral Resources in those aspects of investigation involving engineering geology.

One of the problems inherent in a lakes scheme is that of siltation, which has itself a number of aspects; principal among these are the character and severity of erosion in the catchment, the estimation of probable rates of siltation in proposed storages, and remedial measures such as soil conservation; silt traps, and design of weirs and flood gates. The first of these aspects is covered by reports on soil erosion in the catchment by soil conservation officers of the Agriculture and Stock Section, Department of the Interior and of the Soil Conservation Service of New South Wales (1958); the present report deals with the second aspect - the estimation of probable rates of siltation - with some contribution to the problem of remedial measures, which, however, will be more fully covered by engineers and soil conservation officers.

The investigation by Soil Conservation officers suggests that all three streams involved - Molonglo, Queanbeyan, and Jerrabomberra - will carry a considerable silt load in time of flood; this is a sufficiently clear indication that the siltation problem is real and that investigation needs to be carried a step further to estimate the probable siltation rates in the Lakes: from these can be gauged the probable effect of siltation on the life of the Lakes as ornamental or recreational features.

The fact that the site for the proposed weir in Canberra is itself under current investigation causes little complication in the study of siltation because maximum storage level has been fixed at the 1,825 foot contour level and because suitable weir sites have been restricted to a two-mile strip of the valley from Acton to Yarralumla.

It must be emphasised at this stage that the setting of a deadline for the completion of all pertinent investigations at the end of September has meant that results have been sought by the quickest method and conclusions based on the data obtainable in the time. This report is, therefore, a review of part of the siltation problem, not an exhaustive enquiry.

The assistant of colleagues from the Department of Works is gratefully acknowledged; moreover, notes on siltation made by Mr. F. Waitt of the same Department, in a previous investigation of the problem, have proved very useful.

METHODS IN SILTATION MEASUREMENT

GENERAL

Rates of siltation* in proposed reservoirs may be estimated by three principal methods:

(a) Estimation by applying empirical formulae mainly based on the relationship of storage to catchment area; this may be refined by allowing for trap efficiency**.

(b) Estimation of the silt load carried along the water-courses, modified by allowing for trap efficiency.

(c) Estimation of siltation by c mparing the catchment and proposed reservoir with catchments of existing reservoirs where siltation rates have been established by measurement..

These principal methods can of course be refined and the most reliable results are likely to come from a combination of (b) and (c); consideration of these principal methods is, however, a suitable starting point.

As regards estimation of probable siltation in the proposed Molonglo storage, method (b) cannot be applied as yet because there has been no silt-sampling of any of the streams concerned. A number of turbidity measurements have been made, but consistent silt sampling over at least two years is required before silt transported in suspension can be estimated and the calculation, using these figures, of probable bed load can be attempted, and then not with much confidence.

Of the remaining two methods, (a) - estimation by the application of empirical formulae - may be dismissed as too incorrect for this investigation; these formulae are necessarily based on overseas catchments and silting rates because insufficient measurements have been made in Australia to provide empirical formulae of our own.

Considering the numerous and varying factors such as rainfall, run-off, topography, geology, soils and the severity of soil erosion, which determine siltation rates in any one area, it is obvious that empirical formulae would

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* The terms "silt" and "siltation" refer to the whole range of disintegrated rock material transported by streams.

** Trap efficiency is the percentage of the total incoming sedimentary load trapped or retained by the reservoir.

only be likely to provide reliable results where they are based on catchment conditions similar to those of the catchment under investigation. It is true that with refinements, the method has its uses; Witzig (1944) expanded a method used by the United States Soil Conservation Service (Eakin, 1939) and provided a formula based on measured siltation rates in over 50 reservoirs in the United States of America in which an essential factor is a "regional index" which takes empirical account of regional change in conditions. The method can be useful in providing broad comparisons or first approximatations, but it cannot be duplicated in Australia until the rates of sedimentation in many reservoirs have been measured.

It is noteworthy that siltation rates measured in American reservoirs (and quoted in Witzig, 1944) are, in general, many times higher than the few measured Australian rates which the writer has been able to collect. (Table 1 - see page 5). Other overseas empirical formulae such as those derived by Inglis (1942) and Khosla (1949), when applied to Australian reservoirs where measurements have been made, give high and indeterminate results. One example will suffice: siltation has been measured in the Melton Reservoir (described below) as 116 acre feet per year over a period noted for severe soil erosion (Condon, 1951); Inglis' formula applied to this catchment indicates rates ranging from 46 acre feet per year, if the catchment were rocky, to 510 acre feet per year, if the catchment were largely covered with soil. It seems apparent from this and from Table 1 that siltation rates are generally considerably higher in America and Europe than in Australia, presumably a consequence of contrasts in climate, topography, and population.

In fact, considerable areas of our reservoir catchments are still under virgin forest cover; areas of severe soil erosion normally constitute only small percentages of our drainage areas; and the relief and consequently the stream gradients within our catchments are comparatively low.

However, siltation rates may easily be under-estimated where reservoir surveys are not complete; Witzig (1944) quotes examples, particularly that of the Elephant Butte Reservoir, of early under-estimation of siltation rates because surveys were restricted to the headwaters sections of the storages and did not take into consideration silt already deposited in the remainder of the storage, largely by density currents. As regards siltation rates used later in this report, the Melton figures result from complete survey of the storage; the method of survey at Cunningham Creek is not yet known, but in such a small and largely silted storage the error in estimation is not likely to be significant.

Siltation in the proposed Molonglo storage can then be estimated only by the method of comparing catchments. In this method the comparative figures can approach accuracy only if the catchments compared have the same basic characteristics. These basic characteristics are: size, climate, stream flow and gradients, and supply of debris or silt to the streams, which is a composite factor dependent on geology, geomorphology, soils, vegetation, and land use. An estimation of gross siltation, based on such a comparison, needs to be refined by taking some account of the probable trap efficiency of the storages concerned, particularly where the storage ratios are less than 100-acre feet per square mile of catchment.

TABLE I

COMPARATIVE RATES OF SILTATION IN SELECTED AREAS

Reservoir	Original Storage Capacity per square mile of catchment	Siltation per 100 sq. miles of catchment per year	Source of Data
	(Storage ratio) Acre feet	Acre feet	
United States of America			
Lake Cabot (California)	404.76	174	Eakin (1936)
White Rock (Texas)	159.28	119-136*	Eakin (1936)
Lake Michie (Durham, N.C.)	74.54	17-26*	Eakin (1936)
Gibralter (California)	73.0	80-300*	Eakin (1936)
Zuri (N. Mexico)	31.62	110-121*	Eakin (1936)
Lake Worth (Texas)	25.0	57	Eakin (1936)
Boysen (Wyoming)	2.07	13	Eakin (1936)
Lake McMillan (N. Mexico)	4.09	1-9	Eakin (1936)
Australian Reservoirs			
Pykes Creek (Vic.)	300	90	Victorian Rivers and Water Supply Commission
Hume (Vic. & N.S.W.)	212	20	Victorian Rivers and Water Supply Commission
Eildon (Vic.)	204	2-80* (Av. 15)	Victorian Rivers and Water Supply Commission
Burrinjuck (N.S.W.)	154	6	Works Dept., Canberra.
Melton (Vic.)	44.8	27.4	Condon (1951)
Laanecoorie (Vic.)	8.75	2-11* (Av. 9)	Victorian Rivers and Water Supply Commission
Cunningham Ck. (N.S.W.)	2.0	13.0	Hellstrom (1951)

* Range indicates maximum and minimum rates where measurements have been made over two or more specific periods.

Since no two catchments will have, in fact, the same characteristics, the accuracy of the method will depend on how correctly adjustments can be made to allow for significant changes in basic characteristics. One of these characteristics, size of catchment, is amenable to a simple mathematical adjustment; the adjustment of other characteristics is entirely or in part subjective, so that no two investigators are likely to obtain the same result.

However, properly used the method should indicate a range of siltation rates within which the correct rate is likely to fall, provided that catchment conditions do not change significantly after the forecast was made.

ADJUSTMENTS IN COMPARING CATCHMENTS

Some note on difficulties in adjusting for size, supply of silt and for trap efficiency is pertinent at this stage.

Siltation rates are normally quoted in acre feet per square mile or per hundred square miles of catchments, so that size of catchment is automatically taken into account, in comparison. However, this can lead to error, particularly where large catchments are compared with small ones, because in some large catchments at least a significant percentage of the drainage area may provide little or no debris to the distant storage. For example, comparison of the proposed Molonglo storages with the Burrinjuck catchment should be ruled out on this score, because much of the headwater section of the large (5,000 square miles) attenuated Burrinjuck catchment would contribute no bed load and probably little suspended load to the estimated 130 acre feet of siltation per year in the reservoir. This 130 acre feet of silt would more properly be credited to a much smaller drainage area along the Murrumbidgee and Goodradigbee Rivers and tributaries, upstream from the reservoir; but without considerable field work no attempt can be made to assess the percentage of catchment which is likely to be, in fact, supplying the bulk of the silt. It follows that comparison with much larger catchments than the Molonglo one should be suspect.

Dealing with smaller catchments, it is possible in some cases to refine the comparison by relating siltation rates to restricted areas of significant soil erosion which supply the flood load of the streams. This in effect is differentiating between the man-made "accelerated erosion" and the "geologic norm" (Eakin, 1936) and relating erosion rates to the former. This has been done for the Molonglo and Werribee catchments, but was not feasible for the Cunningham Creek.

The same investigation, the delineating of eroding areas within the catchment, provides some basis for comparing the degree of severity of erosion or the relative silt yield of the catchment; admittedly, this is subjective, particularly where no silt sampling has been done, but where other contingent factors in transport are of the same order - climate, river flow, gradient and distance between eroding areas and storage - subjective adjustments for differences in severity of soil erosion are clearly warranted.

Adjustments for trap efficiency present even more difficulty where storage capacity per square mile of catchment is low, at least less than 100 acre feet, and particularly less than 20 (original storage or effective storage after areas of siltation), an increasing percentage of soil load is passed by the reservoir in flood. For this reason the gross siltation rates for catchments are better estimated from reservoirs with high storage ratios; Eakin (1936) in recording siltation rates in the United States of America, makes a division between reservoirs of "higher capacity-inflow ratio" and those of "small capacity-inflow ratio".

Additional factors affecting the percentage of silt retained in a reservoir are the purpose and control of the storage and the type and performance of flood gates. It is hardly possible to adjust for these latter factors, but some attempt must be made to adjust for trap efficiency in reservoirs with low storage ratios like the proposed Acton and Yarralumla storages, which have storage ratios of 11.8 and 30.8 respectively.

The best way to adjust for this factor appears to be by applying a formula derived by Brown (1944) from a set of curves setting out the relation between percentage of silt retained and the storage ratio. This formula is:

$$CT = \left\{1 - \frac{1}{1 + 0.1\ SR}\right\},$$

where CT = percentage of silt retained, SR = storage ratio (acre feet of storage per square mile of catchment).

The method is, of course, rule of thumb and results are suspect, particularly for reservoirs of very low storage ratios, say less than 10, but the fact that the proposed Acton storage would, by this formula, retain only 54% of the silt delivered to it, emphasises the point that neglect of this factor is likely to result in misleadingly high forecasts of siltation rates. A more refined method of adjusting for trap efficiency has been developed by Churchill (see Maddock and Borland, 1957, p.116) by relating trap efficiency to a "sedimentary index" which is the period of retention divided by the mean velocity; this relation, when modified to take into account the size of the incoming sedimentary particles, has promise of being the best approach to the determination of trap efficiency. However, the basic figures are not available for the application of this formula to the Molonglo catchment at present.

METHOD OF INVESTIGATION

With these points in mind, two reservoirs in which siltation had been measured (Melton and Cunningham Creek) were selected as providing the closest parallel with conditions in the Molonglo catchment. It is hoped that one or two may be found and investigated later, but the time available for this review was sufficient only for the investigation of these two catchments.

The Molonglo catchment was first investigated with particular reference to soil erosion and a photographic record made. Discussion in the field with Messrs. Durham and Hirst, soil conservation officers, and the soil erosion map of the catchment were particularly useful.

The writer then made a reconnaissance of the Werribee River catchment in Victoria and of the Cunningham Creek catchment near Harden, N.S.W.; particular attention was paid to the incidence of soil erosion and photographic records were taken. The characteristics of these catchments are now briefly described and siltation rates discussed as a basis for a forecast of siltation rates in Molonglo storages.

REVIEW AND COMPARISON OF CATCHMENTS

MOLONGLO CATCHMENT

Although the location of a weir at Canberra has not been decided, investigation has centred on two sites - Acton and Yarralumla; in this report siltation is related to these alternative sites. The maximum water level remains the same in both storages, so that the main difference between the alternative reservoirs is capacity. To serve their purpose as lakes, the reservoirs will remain full, although arrangements may be made to drop the level of water before an impending flood to help pass flood water.

Basic figures for the Molonglo Catchment are:

Area of catchment	:	726 square miles
Average annual rainfall	:	20-25 inches
Average annual flow of the Molonglo at weir sites	:	42,000 acre feet
Area producing major flood load	:	78 square miles (10.8% of catchment)
Average distance of these areas from storage	:	8-10 miles
Maximum relief in these areas	:	2,000 feet
Average stream gradient-storage to areas producing major flood load	:	Approx. 40 feet per mile

Proposed Weirs

Acton	Storage capacity	8,600 acre feet
	Storage ratio	11.8 acre ft. per square mile of catchment
	Trap efficiency	54%
Yarralumla		
	Storage capacity	22,300 acre feet
	Storage ratio	30.8 acre feet per sqare mile of catchment
	Trap efficiency	76%

The Molonglo catchment, in general, consists of mature valleys dissecting old land surfaces, remnants of which persist as residual ridges or gently rolling plateaux on the interfluves. There is unmistakeable evidence of old land surfaces and of very slow rates of erosion in the geologic past (Noakes, 1954). A feature of the terrain is the depth of weathering which greatly increases "erodability" particularly in granite, volcanic and shale and limestone areas.

Underlying rocks consist of folded Ordovician sandstone and siltstone, folded Silurian volcanics, shale and limestone and considerable areas of granite. Three major streams drain the catchment: the Molonglo has its upper reaches in granite and in Silurian and Ordovician sediments, but closer to Canberra traverses relatively hard Ordovician sediments. The Queanbeyan River runs for most of its course close to the contact between Silurian and Ordovican sediments with areas of intrusive granite. Much of its catchment overlies sheared Silurian acid volcanics. Jerrabomberra Creek lies mainly in Silurian volcanics and sediments.

Soil erosion is not restricted to specific rock types, largely because of the depth of weathering, but, in general, softer Silurian sediments, sheared Silurian volcanics and granite areas, tend to provide more silt load than do the somewhat harder Ordovician rocks. A large part of the Molonglo catchment is regularly used for grazing sheep and a large part of it is deforested grassland; however, considerable areas retain their forest cover.

Areas of severe soil erosion which supply the major silt load to floods have been worked out from the soil erosion map and total 78 square miles. In this total are combined the areas of deep frequent gullying with varying degrees of sheet erosion, and areas of deep infrequent gullying with moderate to severe sheet erosion. Areas of deep infrequent gullying with only minor sheet erosion have not been included. Isolated patches showing significant soil erosion in the upper reaches of the catchment should not be included because it is very doubtful whether these would in fact contribute significantly to storages at Canberra.

These selected areas are currently eroding although erosion was somewhat more severe in the past when the rabbit population was greater; however, improvement in rates of soil erosion due to decline in rabbit population seem much more marked in the Werribee and Cunningham Catchment than in the Canberra area.

WERRIBEE (MELTON) CATCHMENT

The Melton Weir was built on the Werribee River 8 miles south-east of Bacchus Marsh, 35 miles west-north-west of Melbourne, in 1916. The weir was built by the Victorian State Rivers and Water Supply Commission for storage for irrigation; the structure consists of a 110 ft. high earthern embankment with concrete core and concrete spillway. Spillway gates were added in 1937 to increase the storage capacity from 17,000 to 19,000 acre feet.

The basic figures for the catchment of the Werribee River above the weir are as follows:

Area of catchment	:	424 square miles
Average annual rainfall	:	25 inches
Average annual flow of the Werribee at weir	:	48,000 acre feet
Maximum relief in these areas	:	1200 feet.
Average stream gradient-storage to areas providing major flood load	:	50-60 feet per mile
Area providing major flow load	:	43 square miles (10% of catchment)
Average distance from major eroding areas to storage	:	10-12 miles

Melton Weir

Storage capacity	:	19,000 acre feet (1937)
Storage ratio	:	44.8 acre feet per square mile of catchment
Trap Efficiency	:	82%

The Werribee catchment consists of wooded hills and ridges in its northern portion, approximating half of the total catchment, and grasslands in the southern sector through which flows the principal stream, the Werribee. The grasslands consist largely of rolling plateau country, underlain by Tertiary basalts, into which the Werribee and its tributaries have carved valleys in which are exposed Tertiary and older sediments and igneous rocks.

The northerly portion of the catchment is underlain by folded Ordovician slate and sandstone and in general soil erosion from these areas is slight; in fact in this catchment severe soil erosion is largely restricted to two areas where comparatively soft rocks have been exposed by the stripping of Tertiary basalt cover. These areas are the catchment of the Parwan Creek west of Bacchus Marsh where soft Tertiary sediments - sandstones, limestones and clays - have proved easily erodable and the Pentland Hills a few miles north-west of Bacchus Marsh where Permian mudstones and glacigene sediments, with some Tertiary sediments, have provided a second area of fairly severe soil erosion, although not as prominent as that of Parwan Creek.

Soil erosion in these two areas has greatly improved in recent years, mainly owing to the control of rabbits, but the scars caused by gully and sheet erosion, now largely held by spreading vegetation, clearly indicate the past extent and character of erosion toward the end of the period for which siltation rates in the storage have been measured.

Siltation Rates

Measurements of the storage up to 1948 showed that capacity had fallen from 19,000 acre feet to 15,400 acre feet in 31 years (Condon, 1950). This gives an annual siltation of .274 acre feet of silt per square mile of catchment; if siltation be restricted to the areas where severe erosion is evident the annual rate becomes 2.7 acre feet per square mile of severely eroded country.

Some allowance should be made for trap efficiency; Condon (1950) remarked that it seemed obvious that a considerable amount of sediment was passed by Melton Weir during flood. Based on Brown's formula for trap efficiency (Melton 84%) the gross rates of siltation in the catchment are:

Whole catchment	: 0.327 acre feet per square mile per year
Areas providing major flood load	: 3.22 " " " " " " "

Comparison with Molonglo Catchment

Rainfall, relief and stream gradients in both catchments are comparable. Average annual stream flows are of the same order; it is considered that no correction for this factor should be made without very detailed study of the two environments including silt sampling, because the important factor in siltation is not average annual flow but flood flow when the bulk of the sedimentary load is transported. It may well be that the smaller figure (42,000 acre feet) for the Molonglo reflects a greater "run-in" in the Molonglo catchment, providing replenishments for underground water, which would affect normal flows much more than flood flows.

The factors which need adjustment in the comparison are size of catchment and supply of silt from soil erosion.

The size of catchment can be adjusted by using the ratio of the whole catchment areas or of the areas providing the major flood loads. By coincidence, the resulting adjustments are virtually the same because the eroding areas in both areas amount to approximately 10% of the catchment.

Adjustment for severity of erosion is much more difficult. A comparison is being made between present erosion in the Molonglo catchment and past erosion in the Werribee catchment. Comparison is possible because, as explained above, the extent and character of past erosion is still clearly evident and, moreover, M.A. Condon, who carried out engineering geology investigations in the area during the period of severe erosion, has assisted the writer by comparing present and past conditions of erosion.

The starting point for the comparison is that although there does not seem to be much between the present rates of soil erosion in the two catchments it is fairly obvious that the present rate within the Molonglo catchment is considerably lower than that of the Werribee catchment in the years to which siltation estimates refer. Condon (1950), quoting Forbes (1948), mentions that the Werribee catchment includes some of the worst areas for water erosion in Victoria. The proportion of the Werribee rates to be applied to the Molonglo in the immediate future is admittedly little better than an intelligent guess, but having seen both catchments the writer considers that 50% of the past Werribee rates would be nearer the mark.

It might be emphasised at this point that improvement in soil erosion in the Werribee catchment seems essentially due to decline in rabbit population; a few small silt traps were noticed but these were completely silted up. Erosion rates will rise considerably if rabbits increase; this applies to the Molonglo catchment where rabbits are more plentiful than in the Werribee area, and where control of rabbit population must be recognised as one of the essential controls over siltation rates.

Gross rates of siltation in the Molonglo catchment, by comparison with the Werribee catchment, may now be calculated for both proposed Acton and Yarralumla storages (Table 2). These calculations are finally expressed as ½ and 2/5 life of the storages. It is obvious that most reservoirs cease to fill their purposes long before siltation is complete; the calculations of the ½ life of a storage is common procedure for this reason and because siltation rates may appreciably change when the storage has been so reduced.

In the Acton storage the lake will be naturally divided into three sections by two restrictions of the stream valley; rough calculations by the writer, based on the capacity of these sections of the storage and the likely distribution of sediments suggest that a critical point in storage capacity when the two upper sections cease to fulfil their functions as ornamental lakes (silted up or 3-4 ft. of water), is likely to be reached before ½ life; a second calculation, that of 2/5 life which seems more realistic, is therefore included in the tables.

CUNNINGHAM CREEK CATCHMENT

A small curved, gravity-type concrete wall about 35 feet high was built on Cunningham Creek, 3½ miles south of Harden in southern-central New South Wales in 1913. The purpose of the weir was to supply water to the railway depot at Harden.

Basic figures for this catchment are:

Area of catchment	:	316 square miles
Annual average rainfall	:	20/25 inches
Maximum relief	:	900 feet
Average stream gradient	:	40-50 feet per mile
Area providing major flood load	:	Indeterminate

Cunningham Creek Weir

Storage	:	732 acre feet
Storage ratio	:	2.32 acre feet per square mile of catchment
Trap efficiency	:	17%(?)

The Cunningham Creek catchment consists mainly of gently undulating parkland (grassland areas studded with clumps of trees) with little forest country remaining. The whole catchment is underlain by granite which although showing a number of petrological variations, is normally deeply weathered, providing plentiful debris to eroding streams.

The character and severity of soil erosion is remarkably uniform throughout this granite catchment and falls currently in the class of deep, infrequent gullies, with minor to moderate sheet erosion. Active bank erosion is seen in some sections of the streams. Many of the erosion scars are now held by vegetation, again, largely the result of rabbit control. Erosion rates were certainly higher in the past than they are now but Hellstrom (1951) remarked that "in comparison with other streams in Australia the rate of silting of the Cunningham Creek Reservoir appears moderate."

Siltation Rates

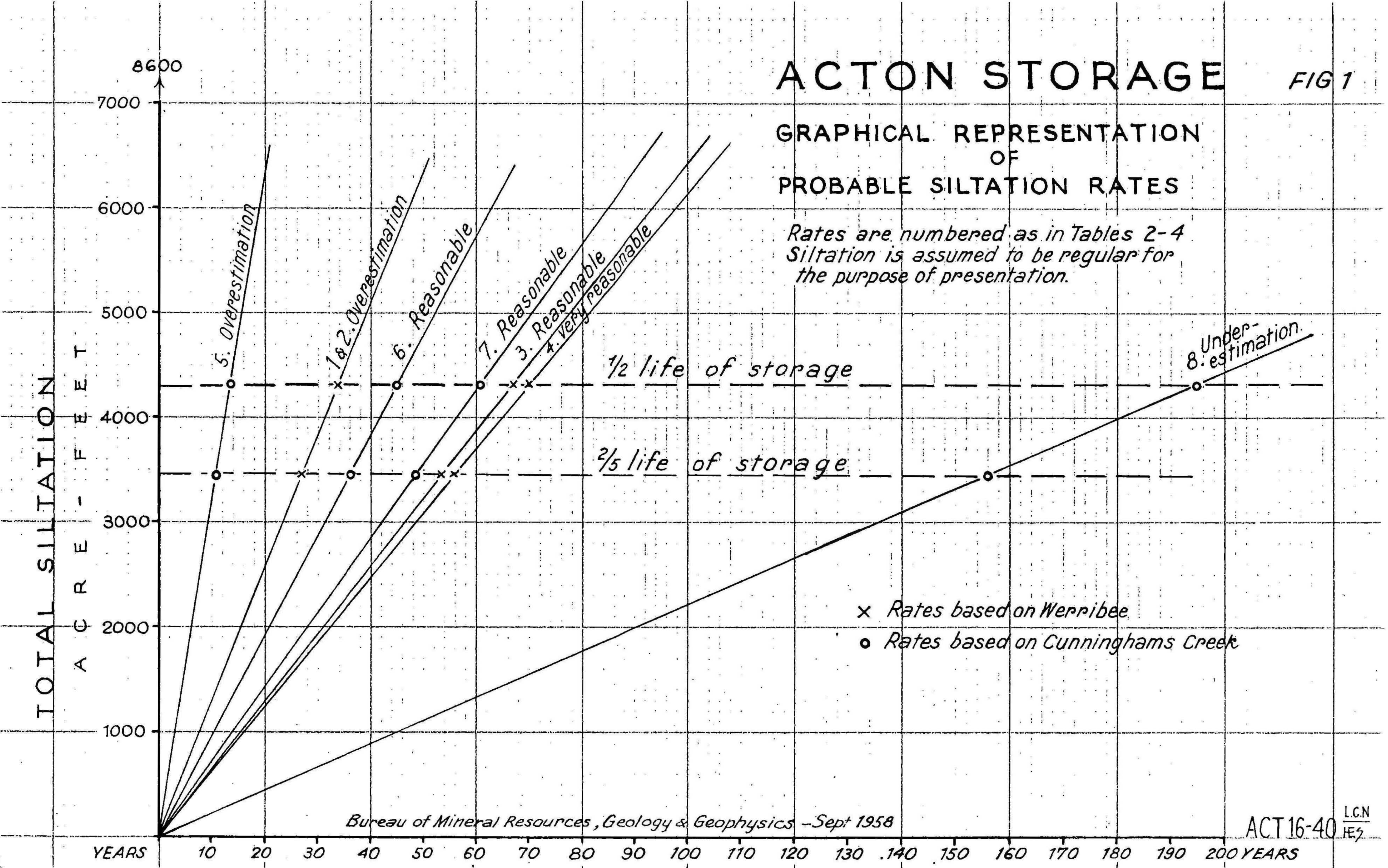
Hellstrom (1951) states that the Cunningham Creek Reservoir was abandoned after 20 years and that the siltation rate for the first ten years was measured as 0.13 acre feet of silt per year per mile of catchment.

Comparison with Molonglo Catchment

The climatic and topographic factors are similar; the Cunningham Creek area with its undulating parkland, with a mantle of deep weathered granite, is geomorphologically similar to much of the Molonglo Catchment. The character of the silt produced in the Cunningham Creek area would be similar to that produced from granitic and acid volcanic areas in the Molonglo catchment, but on the whole the Cunningham Creek debris would have a higher proportion of sand.

The main factors for adjustment in the comparison are area of catchment, severity of erosion, and trap efficiency. Size can be adjusted by the ratio of the areas of catchments; it was not feasible to delineate areas providing major flood loads within the Cunningham Creek catchment, because the pattern of soil erosion was so uniform.

However, it is noteworthy that this catchment does not possess forested areas where soil erosion is minor or negligible, i.e. little or nothing of the "geological norm"; for this reason a simple adjustment for size by



ACTON STORAGE
FIG 1
GRAPHICAL REPRESENTATION OF PROBABLE SILTATION RATES
Rates are numbered as in Tables 2-4
Siltation is assumed to be regular for the purpose of presentation.
TOTAL SILTATION ACRE - FEET
8600
7000
6000
5000
4000
3000
2000
1000
YEARS
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200 YEARS
5. Overestimation
1 & 2. Overestimation
6. Reasonable
7. Reasonable
3. Reasonable
4. very reasonable
8. Under-estimation.
1/2 life of storage
2/5 life of storage
× Rates based on Werribee
o Rates based on Cunninghams Creek
Bureau of Mineral Resources, Geology & Geophysics - Sept 1958
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catchment areas must tend to over-estimate siltation rates in the Molonglo. A preferable adjustment would relate Cunningham Creek rates to the eroding catchment in the Molonglo area; for this purpose the areas in the Molonglo catchment showing deep, infrequent gullying with moderate sheet erosion plus areas of more severe erosion were combined on the soil-erosion map, with a total area of 170 square miles. This will tend to underestimate Molonglo rates but should be nearer the truth than the first adjustment for size.

On severity of erosion there is little doubt that the present siltation rates in the Molonglo catchment are higher than those at Cunningham Creek. In the past, however, these have been considerably higher, although they were probably not as high as those applicable now to the 78 square miles previously calculated for severe erosion in the Molonglo catchment. The best way of handling the comparison seems to be to accept the Cunningham Creek rates as they stand and make adjustments to the area of Molonglo catchment to which they might apply.

The adjustment for trap efficiency, like that for size of catchment, is a real problem. According to Brown's formula, the efficiency of the Cunningham Creek reservoir would be only 17% - a figure which one feels is too low; the formula is least likely to be accurate when applied to reservoirs of such low storage ratios. Moreover, the Cunningham Creek Weir is a concrete wall with no flood gates, so that maximum trap efficiency for the storage should be obtained. One way of handling the problem would be by calculating two rates -

(1) Rates assuming a trap efficiency of 17%, which would tend to over-estimate or give a maximum figure;

(2) rates assuming the trap efficiency of the proposed Acton Weir, which might approach a minimum figure or underestimate as the Cunningham Creek Weir would not be likely to trap a higher proportion of silt than the proposed Acton storage.

Possible siltation rates for the Molonglo catchment on these bases, with alternative adjustments for size and trap efficiency, are given in Table 3; the alternative adjustments for size and trap efficiency provide a bracket of rates, the two outermost of which are regarded as the least reliable.

DISCUSSION OF POSSIBLE SILTATION RATES IN THE ACTON STORAGE

(Table 4, Fig. 1)

The first relatively simple comparison between the Molonglo catchment and two similar catchments indicate net siltation rates in the Acton storage of 300 or 128 acre feet per year, or expressed in 2/5 life, 11 years or 27 years (see Table 4). Both may be confidently regarded as over-estimates; one, because of obvious difference in the severity of erosion (Werribee); the other because of two factors - size of catchment and trap efficiency - both lead to over-estimation. The indication is that the rate for Acton should be lower than 128 acre feet per year and the 2/5 life greater than 27 years.

More correct figures are sought by refining the comparisons where this can be done; rates derived from the Werribee catchment are likely to be more reliable than those derived from Cunningham Creek, because the refinement is virtually restricted to one factor - severity of erosion. Admittedly, this refinement is a subjective one, but it can be checked by other workers. The writer's feeling is that the application of half of the Werribee erosion rate to eroding areas in the Molonglo catchment is a reasonable adjustment and tends to underestimate rather than overestimate.

Refined rates, based on Werribee, would then indicate siltation of the order of 60 or 70 acre feet per year in Acton storage (rates 3 and 4), giving a 2/5 life of the order of 50 to 60 years. Attempts to refine the rates from the Cunningham Creek catchment with two variables provides a wider spread of possible rates (numbers 6, 7 and 8), of which one (8) is obviously an underestimation. The other two, resulting from adjustments in which the two variable factors are opposed, appear more reliable in that errors tend to cancel themselves out. It is difficult to assess the significance of these rates (6 and 7), 95 or 70 acre feet per year or 36 or 49 years for 2/5 life, but they provide some general confirmation for more reliable rates derived from Werribee figures.

An assessment of the two sets of rates would indicate that siltation in the Acton storage is likely to be of the order of 50 to 100 acre feet per year; within that range 60 to 70 acre feet per year or 2/5 life of 50 to 60 years may be suggested as a preliminary estimate.

ACTON VERSUS YARRALUMLA AS A WEIR SITE

The probable rates of siltation derived above appear to favour the Yarralumla site for the weir because of the difference in half life of the respective storages. However, this difference is more apparent than real because the vital portion of the Lake Scheme, in the city area, forms the head of storage and will be the obvious area to receive silt whether the weir is located at Acton or farther downstream.

There would, no doubt, be differences in the pattern and extent of siltation in the two storages, but these are very difficult to assess on theoretical grounds; in fact, one of the uses of the model of the Lake Scheme at present under construction should be the investigation of silting in the headwater area in relation to alternative weir sites.

In theory there are two factors which suggest that changes in the weir site will involve changes in siltation; these factors are opposed and will tend to cancel themselves out. In the first place the Yarralumla storage should retain some $1\frac{1}{2}$ times the amount of silt retained by the Acton storage on the basis of trap efficiency. Much, but not all, of this additional silt will be fine sediment, normally passed by the Acton storage; additional silt of fine to medium sand grain size would probably tend to accumulate near the head of storage.

In an opposite sense, density currents, the second factor, would certainly be more effective in the Yarralumla storage than in the Acton storage because the lake would be deeper and would provide more contrast in turbidity. These currents, directed by the restrictions in valley profile at Acton and above would almost certainly transport silt of mixed grain sizes down gradients to the deeper portions of the reservoir and even to the dam itself.

As there is no way of theoretically determining the carrying capacity of density currents, one is forced to conclude that, as far as siltation is concerned, there is no present basis for preferring one weir to the other. The problem may be resolved by the model, although density currents will be difficult to induce in shallow water flows.

REMEDIAL MEASURES

Siltation rates of the order of those indicated in this review, establish the siltation problem, as the most important single problem to be faced in initiating the Canberra Lake Scheme. Remedial measures now assume equal importance.

This is primarily the field of soil conservation and land use; after reviewing engineering methods of reducing siltation in America, Eakin (1936) remarks that "in contrast with these inefficient and objectionable measures, the permanent reduction of silt content in the contributing streams by means of erosion control practices .....has been abundantly demonstrated. Erosion control not only has the effect of conserving lands in the watershed but is outstanding as the one fundamental and permanently practical means of reducing the rate of reservoir silting".

Nevertheless, engineering methods of reducing siltation have their place, because although they lack permanency, they can achieve almost immediate results where soil husbandry takes more time to become effective. The proper design of flood or sluice gates in the weir is probably the most effective and most permenent engineering contribution to the problem. Silt traps or siltation weirs on the principal streams constitute another obvious method of reducing reservoir silting but to be effective these weirs would need considerable depth, otherwise, like the Queanbeyan Weir, their trap efficiency would be too low to protect the main storage.

If more permanent protection were planned for the future, it might be economic to build a substantial multi-purpose weir or weirs to serve primarily as siltation weirs for a number of years, until erosion control took effect; thereafter they would have sufficient remaining storage to continue to serve as flood or river control weirs.

There is another method which warrants some further investigation. Although dredging as a method of silt control is rightly regarded as the last resort because of the cost of winning and disposing of the material, it falls into a different category if the material dredged can be economically used. The writer has persistently urged that sand pumping should be tried on some of the sand deposits at and below water level in the Molonglo, notably near the Canberra Power House, as a method of working deposits which are in part replenished by the river. It is suggested that similar dredging might be carried out in delta deposits at the head of storage when the lake is established.

There is no doubt that the Molonglo and Jerrabomberra Creek, particularly the latter, will provide a considerable quantity of sand from their bed load alone, which will be the main constituent of the deltas. Removal and washing of this sand could help to preserve storage and provide useful building material in the same action.

Looked at another way, the bulk of Canberra's local sand supplies lies along the stretch of the Molonglo between Yarralumla and the Abattoirs. Completion of the Lake Scheme will rob Canberra of much of this local supply, with the result that sooner or later the cost of river sand in Canberra will rise by the cost of cartage from the Murrumbidgee. When this occurs the additional cost of dredging sand from the deltas could reach the cost of cartage - say 17/- per yard on present costs - before the product ceased to be competitive or before some of the cost would need to be debited to silt control.

Admittedly more investigation is required as to the probable composition of delta deposits; investigation of deltas in the Burrinjuck storage, as well as of present Molonglo deposits, seems well warranted. It might be necessary and economic to provide low concrete sand traps, like the present Power House Weir, near the mouths of the contributing streams to produce cleaner sand, but it is hoped that model studies will help in this aspect, as well as in the character and extent of delta formation.

In the matter of quantity, Canberra's present demand for river sand, 40,000 to 50,000 cubic yards per year, amounts to 25 to 30 acre feet. An assumed annual retention of 60 to 70 acre feet of silt in the Acton storage would probably supply enough sand but it would not all be in dredgable delta deposits, so that it seems, at the present stage of the investigation, that only part, but probably a significant part, of Canberra's supply of river sand could be met by dredging; at the same time this would do much to preserve reservoir storage.

REFERENCES

BROWN, C.B., 1944 - Discussion on paper "Sedimentation in reservoirs" by Berard J. Witzig, Trans.Am.Soc.Civil Eng. 109.

CONDON, M.A., 1951 - The geology of the lower Werribee River, Victoria. Proc.Roy.Soc.Vic. 63.

EAKIN, H.M., 1939 - Silting of reservoirs. Tech. Bull. 524, U.S. Dept. Agriculture (revised).

FORBES, I.G., 1948 - Erosion on Melton Reservoir Catchment. State Rivers and Water Supply Commission Victoria (unpublished).

HELLSTROM, B., 1951 - International Association of Hydraulic Research, Meeting BOMBAY 1951, "Solids in stream flow".

INGLIS, C., 1942 - Engineering, 10-4-1942, p.283.

KHOSLA, A.N., 1949 - Water storage conservation techniques. Civil Engineering and Public Works Review, Aug. 1949, p.444.

MADDOCK, T., and BORLAND, W.M., 1951 - Sedimentation Studies for the planning of Reservoirs by the Bureau of Reclamation. _Quatrieme Congres des Grands Barrages, New Delhi_, 1951.

NOAKES, L.C., 1954 - The Canberra region; _in_ Geology and Geomorphology, CANBERRA, A NATION'S CAPITAL, Part 2. _Aust.Ass.Adv.Sci. Sydney_, 1954.

WITZIG, B.J., 1944 - Sedimentation in Reservoirs. _Trans. Am.Soc.Civil Eng._ 109, p. 1047-1071.

TABLE 2.

MOLONGLO CATCHMENT

SILTATION RATES BASED ON WERRIBEE CATCHMENT

GROSS SILTATION RATES IN CATCHMENT

Based on	Werribee Catchment	Molonglo Catchment			
		Adjusted for area of catchment		Adjusted for severity of erosion (50%)	
	Acre/ft. per year per square mile	Acre/ft. per year per square mile	Total Siltation per year Ac/ft.	Acre/ft. per year per sq. mile	Total Siltation per year Ac/ft.
Whole catchment	.327	.327	(1) 237	.63	(3) 118
Eroding Areas	3.22	3.22	(2) 234	1.61	(4) 117

NET SILTATION IN STORAGES

Acton Weir

(Storage - 8,600 acre feet)

Gross Rates Ac/ft. per year	Net Siltation (Trap efficiency 54%) Ac/ft. per year	Annual Reduction in Storage %	½ Life of Storage Years	2/5 Life of Storage Years
(1) 237	128	1.49	34	27
(2) 234	126	1.47	34	27
(3) 118	64	.745	67	54
(4) 117	63	.715	70	56

Yarralumla Weir

(Storage - 22,300 acre/ft.)

Gross Rates Ac/ft. per year	Net Siltation (Trap efficiency 76%) Ac/ft. per year	Annual Reduction in Storage %	½ Life of Storage Years	2/5 Life of Storage Years
(1) 237	180	.81	62	49
(2) 234	178	.8	63	50
(3) 118	89.5	.4	125	100
(4) 117	89	.4	125	100

TABLE 3

MOLONGLO CATCHMENT

SILTATION RATES BASED ON CUNNINGHAM CREEK CATCHMENT

GROSS SILTATION RATES IN CATCHMENT

Cunningham Creek Catchment			Molonglo Catchment	
Ac/ft. per year per sq. mile	Trap Efficiency	Gross Siltation Rate Ac/ft. per sq. mile per year	Adjusted for area of catchment Ac/ft. per year	Adjusted to 170 sq. miles Molonglo Catchment Ac/ft. per year
.13	17%	.765	(5) 555	(7) 130
	54%	.241	(6) 175	(8) 41

NET SILTATION IN STORAGES

Acton Weir

(Storage - 8,600 acre/ft.)

Gross Rates Ac/ft. per year	Net Siltation (Trap efficiency 54%) Ac/ft. per year	Annual Reduction in Storage %	½ Life of Storage Years	2/5 Life of Storage Years
(5) 555	300	3.5	14	11
(6) 175	94.5	1.1	45	36
(7) 130	70.0	.815	61	49
(8) 41	22.1	.257	195	156

Yarralumla Weir

(Storage - 22,300 acre/ft.)

Gross Rates Ac/ft. per year	Net Siltation (Trap Efficiency 76%) Ac/ft. per year	Annual Reduction in Storage %	½ Life of Storage Years	2/5 Life of Storage Years
(5) 555	422	1.9	26	21
(6) 175	133	.6	83	67
(7) 130	99	.445	112	90
(8) 41	31	.14	356	286

TABLE 4

Probable Net Siltation Rates - Acton Storage

Rates (from Tables 2 & 3) Acre-feet per year	Annual Reduction in Storage %	½ Life of Storage Years	2/5 Life of Storage Years	Derivation	Remarks
1. 128	1.49	34	27	Werribee - whole catchment full erosion rates	Over estimation
2. 126	1.47	34	27	Werribee - eroding areas, full erosion rates	Over estimation
3. 64	.745	67	54	Werribee - whole catchment ½ erosion rates	Reasonable
4. 63	.715	70	56	Werribee - eroding areas ½ erosion rates	Very reasonable
5. 300	3.5	14	11	Cunningham Creek - whole catchment. Trap efficiency 17%.	Over estimation on both counts.
6. 94.5	1.1	45	36	Cunningham Creek - whole catchment. Trap efficiency 54%.	Reasonable - adjustments opposed.
7. 70	.815	61	49	Cunningham Creek - 170 square miles. Trap efficiency 17%.	Reasonable - adjustment opposed.
8. 22.1	.257	195	156	Cunningham Creek - 170 square miles. Trap efficiency 54%.	Under estimation on both counts.