The impact and economic effects of soil conservation practice on river aggradation

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ABSTRACT This paper discusses the hydrological, sedimentary and economic consequences of soil erosion in the agricultural drainage basin of the South Johnstone River in Northern Australia. Detailed analyses have been undertaken to estimate historical river changes from aerial photographs. Two-dimensional unsteady mathematical modelling of the rivers and flood plain has been undertaken with the changing cross sections and the differences in modelled flood levels reflect the effect of the aggradation. The economic consequences of these changes were evaluated using urban and rural damage models. Land use changes were evaluated and soil erosion rates were used to obtain order of magnitude estimates of total sediment runoff in the drainage basin for comparison with estimates of sediment accumulation.

INTRODUCTION

Soil conservation scientists have long expressed the view that soil loss reduces productivity and is therefore a cost to the community. A recent review (Mullins et al, 1984) highlighted soil loss in cane growing districts of Queensland and reported rates as high as 382 t ha^{-1} $year^{-1}$. Farmers located near major and minor streams have frequently lamented the damaging effect of this soil loss on the river behaviour. Material from eroded soil is deposited in the streams causing bed aggradation and/or the formation and growth of spits and islands. Vegetation growth in the deposited material accentuates the capture of material in future flood events and accelerates the spit and island growth. Damages (and hence costs to the community) can result from erosion of the stream banks as the stream adjusts to the altered regime, increased flood levels due to the constriction in the stream and poor drainage due to the bed aggradation.

Engineers in flood management analyses of significant Australian flood plains have recognised this problem and modelled the beneficial effects of material removal (Connor et al, 1981, 1982, 1984). Benefits have been modelled in economic terms but in all such studies the costs of the works have outweighed the benefits and hence such works have not been attempted. It appears reasonable then that the initial cause of the problem must be attacked by soil conservation. Soil conservationists have recognized the additional costs but without the weight of actual cost estimates, these arguments have been regarded by policy-makers as speculative. Conversely, the addition of realistic flooding and drainage costs should strengthen the arguments for soil conservation measures.

In an attempt to quantify the additional costs of river aggradation due to the increased risk of flooding, Cameron McNamara were awarded funds under the National Soil Conservation Program to study the effects of soil loss in the drainage basin of the South Johnstone River in Northern Australia.

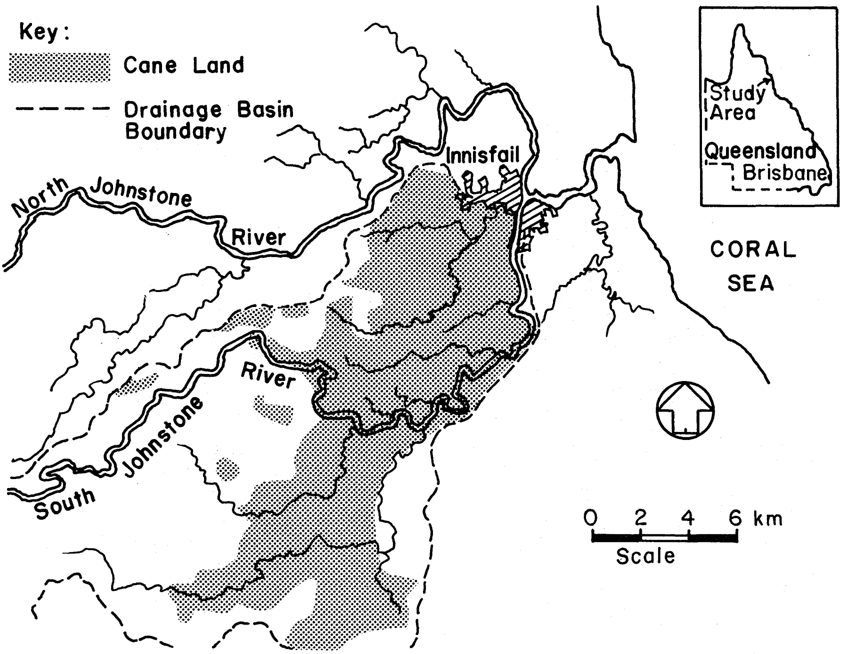

Fig. 1 South Johnstone drainage basin.

STUDY AREA

Some of the highest recorded soil movements in Australia have occurred in the canelands of the Innisfail region in North Queensland. The principal reasons for this are the very high rainfall (totals and precipitation rates), the steepness of some of the farmed land, the erodibility of the soil material and the general non-implementation of good soil conservation practice. Although large loss rates are recognised, the fate of the eroded material has never been established nor have the consequences been evaluated. Local experience points to instances of heavy deposition on roadways at stream crossings, silting up of local drainage channels, loss of historical swimming holes and silt laden flows in the river and estuary.

The particular stream examined in the study is the lower reaches of the South Johnstone River, covering approximately 25 km of river, and the drainage basin is shown in Fig. 1. The river drains a 530 km^2 basin before joining the Johnstone River and flowing for approximately 5 km to the sea. Within the study reach, the river receives local tributary inflows from some 170 km^2 of sub-basins, containing in 1983 some 97 km^2 of assigned cane land. If aggradation causes additional flood damages, urban damages can accrue at Innisfail, situated around the junction of the two rivers, and at Mourilyan, a township supporting a sugar mill some 7 km upstream of the junction.

The predominant industry is sugar cane and the 31 000 ha of cane is mostly grown on alluvials, metamorphics or basalts with the latter two being prone to erosion on the steeper slopes. Rainfalls can be very high: for example mean annual rainfalls are 3641 mm at Innisfail and 2625 mm at Millaa Millaa in the upper catchment. The highest recorded rainfall at Innisfail since 1881 is 7729 mm in 1979 and the highest recorded monthly rainfall is 3459 mm in January 1981.

Eroded soil is transported through the basin and deposition is likely to occur in any of five different environments: elsewhere on the farm, within local drainage routes, within the creek system, in the river environment or in the estuary. Whatever remains in suspension is then transported to sea. Of particular interest in this study was the process and consequences of deposition in the river system.

The river acts as the collector of all of the subcatchment streams (creeks) and as such receives, sorts, deposits and transports all the sediment conveyed to it by its tributaries. In this case, the South Johnstone River enters the study area already carrying the sediment supply from some 350 km^2 of upper basin area. However most of this area is relatively undeveloped and will be delivering sediment at a rate consistent with natural water erosion of the landscape. In this catchment however the river load is significantly added to by the high sediment load of the creek sub-basins of the downstream agricultural areas. Local observers for example recall the South Johnstone "flowing red" after heavy local rainfall: an indication of the high silt load emanating from the local basalt soils. The river in flood has an enormous capacity to transport silts, usually much in excess of the natural supply, and it is likely that a large proportion of the very fine sediment is carried through the river system.

When these high sediment loads are combined with the normal load of the river, the river selectively deposits an amount in excess of its carrying capacity. The amount and grading of material deposited depends on the physical characteristics of the river with material often trapped in vegetation supported by previous depositions. Whereas sand deposited on the bed may be remobilised by major floods, the vegetated spits and islands as currently evident in the South Johnstone River can be considered a stable component of the river topography.

The effect of such deposition is many fold. The formation of stable spits (extension of the bank normally at a level above the low flow water surface) and islands results in a smaller cross section being available for the passage of flood flows. This has two effects: the raising of flood levels for a particular discharge and the raising of velocities at a particular water surface level because of the increased flood slope. Both effects can cause damage. The higher flood levels result in greater and more damaging inundation and the higher velocities could cause slightly more damage to crops. Of the two however the former would be the most significant.

ESTIMATING HISTORIAL RIVER ACCUMULATION

The major source of information on historical river changes is the available aerial photography. The earliest set was flown in 1942 with following sets in 1957, 1977 and 1983. Scales varied from 1:12 000 to 1:46 000. In all photographic sets, a number of points of known coordinates were identified in each photograph. The location could be identified in all photographs and the exact coordinates were obtained from available mapping of the area constructed from the 1983 photography. A digitising process, using the MOSS computer program, established the best fit of the known coordinates to determine the coordinate frame for any other features in the photograph.

The purpose of the exercise was to digitise the South Johnstone River and hence determine changes over time. The boundaries of the river were digitised in each photograph to portray the "wet plan area" in each case. Spits or point bars and islands in the stream were

TABLE 1 Wet area sub-totals and percentages of base year area

Zone Grouping	Base Year	Area (m^2) in Each Year 1942	1957	1977	1983
1		-	563 750	523 720	517 350
	1957	-	100%	93%	92%
2		362 220	344 480	344 130	335 300
	1942	100%	95%	95%	93%
3, 4, 5		539 030	518 120	491 270	455 100
	1942	100%	96%	91%	84%
6, 7, 8		630 110	546 900	528 780	445 140
	1942	100%	87%	84%	71%
9		127 760	-	75 170	61 140
	1942	100%	-	59%	48%
2 to 8	1942	1531 360	1409 500	1364 180	1235 540
		100%	92%	89%	81%

To attempt to evaluate the historical trend of this accumulation, the totals in Table 1 can be plotted as in Fig. 2.

included in the dry area and hence the boundaries were included in the digitised data. For consistency, it was decided to map the boundary as the edge of the vegetated bank. Unvegetated sand surfaces were included in the wet area since they may become mobile in subsequent flood events. Also it was likely that some sand islands could be inundated at high water levels, either during a high tide or at a higher stage in the river. By including only the vegetated area, the boundaries were clearly defined. Also this process meant that a consistent approach would be adopted in all the years of digitising.

The reach of river under study was split into five convenient reaches for mapping and nine different zones for final comparison. Reproductions of the digitised data were compared on a equal scale to show the changes that have occurred in the time span from 1942 through 1957, 1977 to 1983. This process highlighted deposition that has occurred especially in relation to islands, spits or dramatic river bend changes. In the upper reaches, examples of spit and island formations are more common and the general impression is one of an effective narrowing of the river section. Some relatively major changes have occurred, for example one river bend altered considerably from 1957 to 1977 and the stretch of river in one section of the upper reach has narrowed considerably.

To comply with the objective of determining the overall reduction in river channel, the digitised wet area boundaries were used to calculate the total surface area in the various zones. These zones were lumped together in regional groups to obtain an overall picture and Table 1 lists the zone totals and percentage of originally assessed area. Zone numbering increases in the upstream direction. The trend indicated by Table 1 is that accumulation as a percentage of original size is occurring at a greater rate in the upstream areas. Comparing 1983 with 1942, the percentage size varies from

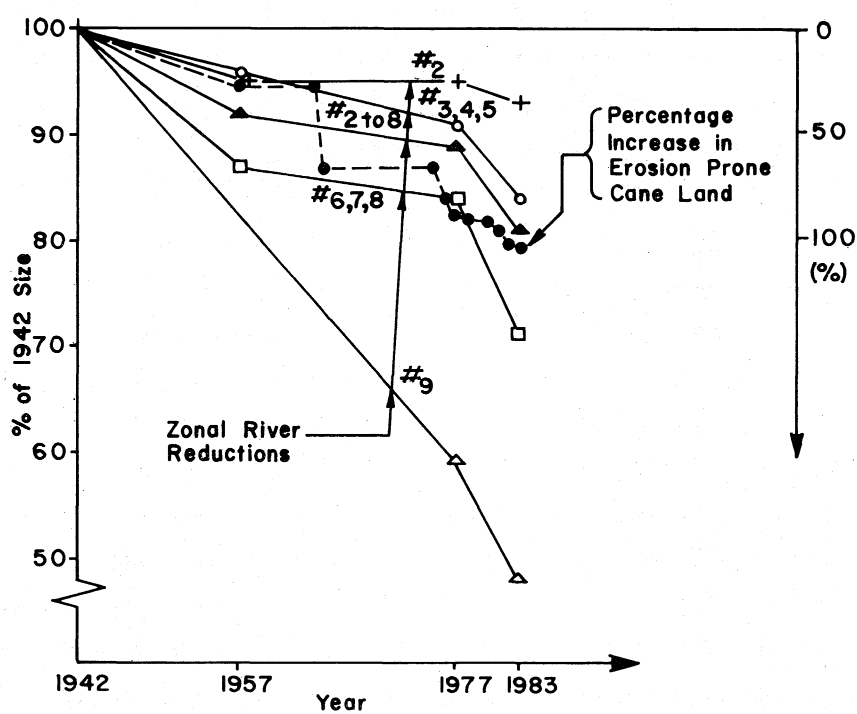

Fig. 2 Historic river accumulation and land use change.

approximately 90% in the lower reaches, through 84% in the middle reaches to 71% and then 48% in the upper reaches. The final set of figures in Table 1 represents the total of known data, that is, for the total reach containing zones 2 to 8. These represent the average change in the South Johnstone River system.

There are some slight inconsistencies in the trends but generally they indicate that accumulation had occurred at a reasonably steady rate from 1942 through 1957 to 1977 but that the rate increased markedly from 1977 to 1983. In terms of the criteria used in measuring the change, Table 2 summarises the rate of change of total wet area in zones 2 to 8.

These figures indicate a recent rate of accumulation some four times the average from 1942 to 1977 and three times the average rate

TABLE 2 Historical reduction in wet area

Period	Reduction (m^2)	Rate (m^2/a)
1942 - 57	121 860	8 120
1957 - 77	45 320	2 270
1977 - 83	128 640	21 440
1942 - 77	167 180	4 780
1942 - 83	295 820	7 215

that has occurred from 1942 to date. It should be noted however that trends evaluated over short time spans are more prone to error than long term trends. The former can suffer from short term influences for example a particular flood event. Therefore it is generally more acceptable and conservative to base opinion on the long term average change. Nevertheless on the basis of the data available it should be remembered that the current rate of accumulation may be of the order of three times that average trend.

MATHEMATICAL FLOOD MODELLING

As part of a recent flood management study conducted for the area (Cameron McNamara, 1985), cross sections were surveyed at regular intervals and a comprehensive mathematical model was established of the area. A series of floods in both rivers of the system were routed through the model to evaluate possible flood mitigation alternatives. The cross sections surveyed in 1983 are input as topographic data to the model and the computer program, called CMCELLS, is able to route recorded flow events through the system, taking into account overbank flow, backwater effects in side catchment storages and combined flow (at the junction) and tidal effects. Historical floods which had been modelled included the 1967 and 1977 floods which are considered to be the equivalent of once in 50 years and once in 10 years floods respectively.

To evaluate the flooding consequences of river aggradation since 1942, it was necessary to simulate the removal of deposited material from the sections surveyed in 1983. The findings discussed earlier offer the best indicator of 1942 river sections and were used to develop the 1942 topographic model.

The findings of the photographic digitisation enable the average width change at normal water level to be determined. For the representative cross-section this change would be applied as a removal of the low level spit on the side of the section that is aggrading. Although the aerial work can give no indication of bed level changes, the bed of the section was adjusted slightly to suit the existing profile on the unaltered side and the new profile on the other. Resultant bed level changes were small. From local comments it is highly likely that bed aggradation is significant and hence the findings of this study in this respect may be conservative.

The altered cross sections were their input to what might be called the 1942 South Johnstone model and the floods representing the 50 year and 10 year floods were routed through the system. These results represent the expected flooding behaviour if no aggradation had occurred since 1942, that is, as if the South Johnstone river had been in a perfectly balanced sediment budget situation. In comparing these results with 1983 results, any increase in levels in the latter case can thus be attributed to South Johnstone aggradation.

Table 3 records the peak flood levels for both flood events and both the 1942 and 1983 conditions. The tabulated levels are those modelled at increasing distances upstream from the river mouth.

The differences for both floods are very similar because the effective changes of cross-sections occur at a lower level than the peak flow profile. Thus the flood level increases begin at low flows and continue throughout the range. Fig. 3 plots the levels for the 50 year flood for a typical location. The increase in flood level is 1.2 m at the peak of the flood and about 1.0 m at lower stages although differences of up to 1.3 m occur.

TABLE 3 Flood modelling results

Location Number	10 Year Flood Levels (m) 1942	1983	Increase	50 Year Flood Levels (m) 1942	1983	Increase
1	3.49	3.58	.09	3.74	3.79	.05
2	3.83	3.97	.14	4.08	4.17	.09
3	4.08	4.37	.29	4.90	5.26	.36
4	4.58	5.04	.46	5.40	5.79	.39
5	5.12	5.66	.54	5.82	6.25	.43
6	5.82	6.48	.66	6.46	6.96	.50
7	6.52	7.50	.98	7.15	7.91	.76
8	7.33	8.51	1.18	8.07	9.04	.97
9	7.82	8.83	1.01	8.54	9.40	.86
10	8.77	10.04	1.27	9.41	10.61	1.20
11	9.33	10.66	1.33	9.93	11.21	1.28
12	9.66	10.53	1.17	10.26	11.41	1.15
13	10.30	11.26	.96	10.89	11.86	.97
14	11.19	12.21	1.02	11.76	12.82	1.06

ECONOMIC EFFECTS

The detailed modelling work discussed previously has been able to identify the flood behavioural changes caused by river aggradation. It is therefore fruitful to pursue the economic consequences of the worsening flood pattern. The economic losses from soil erosion have long been recognised by governments and farmers. In almost all studies to date economic investigations have concentrated on on-farm losses and other directly related effects. The focus of attention of this research is not on this traditional area of interest. Rather, here the economic investigations are directed towards a valuation of the increase in flood losses resulting from soil erosion.

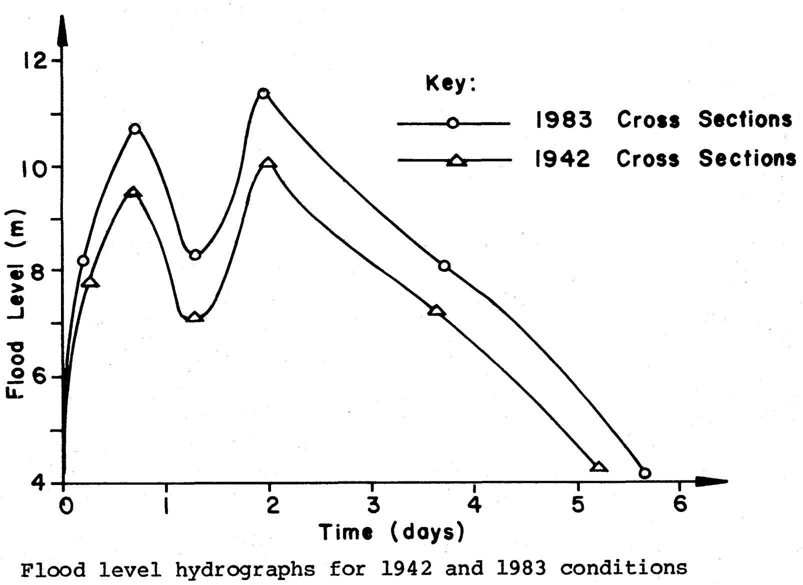

Fig. 3 Flood level hydrographs for 1942 and 1983 conditions

The objective of the research is to estimate the additional flood damages experienced by the total community from river aggradation. The valuation sought is the difference between the expected value of flood damages "with" aggradation and "without" aggradation. The results are intended to provide indicative estimates of the change in flood damages. In common with most similar studies some simplifications and approximations have been made because of data and time constraints.

Urban Damages

The impact of the increased risk of flooding on urban properties is evident in the increased number of properties inundated by a once in 50 year event. Residential properties affected increase from 85 to 167 and business properties from 31 to 68. Table 4 presents the results of an analysis of the expected future damages to the town of Innisfail arising from river aggradation. The values shown are the present worth of the estimated damages during the period from 1983 to 2024. This period length was selected so as to give an equal length period to that in the previous historic damage estimates thereby allowing ready comparison. Table 4 values should be increased by approximately 25% to allow for other urban developments in the study area. Two cases are treated in the analysis: a "low" case, based on the assumption that the increase in flood height between 1983 and 2024 will equal that between 1942 and 1983, and a "high" case, based on the assumption that the increase in flood height will be double that between 1942 and 1983.

TABLE 4 Present worth of future urban damages caused by aggradation ($'000)*

Case	Discount Rate (%)		
	5	7	10
"Low"	340	230	130
"High"	810	560	310

* Note: All dollars refer to Australian dollars

Rural damages

It should be remembered that this study is limited to addressing the consequences of river flooding and hence has not attempted to address the significant local flooding effects caused by deposition within the local catchment. Of special relevance to rural damages is Fig. 3 which shows the flood level variation at cross section 30 over the range of flows experienced in the 1967 flood which has been taken as typifying a once in 50 year event. This indicates that modelled differences occur typically over the full range of flows and not only at the peaks. Thus the peak differences throughout the river reach as listed in Table 3 can also be applied to moderate to major flood levels. The consequence of aggradation is therefore easy to quantify in terms of inundation levels but agricultural damage costs are complicated by the dependence on other factor such as times of submergence, maturity of the crop and silt and velocity effects.

Table 5 lists the times of submergence experienced over a range of levels near cross section 30 for both the 1942 and 1983 conditions.

TABLE 5 Submergence times in once in 50 year event

Level (m)	Duration of Submergence (hours) 1942 Conditions	1983 Conditions	Difference (hours)
5.0	113	127	14
6.0	101	115	14
7.0	85	101	16
8.0	52	86	34
9.0	26	57	31
10.0	4	31	27

The lack of detailed ground level information throughout the basin means that the total situation cannot be evaluated. However using the results from the sample area, it is expected that cane losses could be increased by up to 20% and that such increased losses may occur on a once in 5 year basis. Based on 1977 losses of 11 000 tonnes, the marginal cost of aggradation is therefore estimated at 2 200 tonnes of cane per 5 year period or 440 tonnes per annum. Using a value of $20 per tonne, this represents a figure of $8 800, say $9 000 per annum.

The cost of maintenance activities due to excess siltation is difficult to assess separately from other activities but based on local opinion and assessment of the relative sedimentation character in both river catchments, an estimate of $14 000 per annum appears reasonable. Summation of the calculated agricultural and maintenance costs leads to an estimate of $23 000 per annum. Based on a discount rate of 7%, the present worth of this cost of soil erosion is $330 000.

FARM EROSION CONTRIBUTION TO RIVER DEPOSITION

The preceding analysis indicates large aggradation rates and significant economic consequences. Because the upper sub-basin is relatively undeveloped, one would expect that the local agricultural activities have contributed significantly to the excess sediment supply. An analysis of the historical land use changes was carried out with special emphasis on cane land expansion into the more erodible soils. For the 1983 situation, the total cane land in the drainage basin amounted to 9700 ha, with 5490 ha considered to have high erosion susceptibility. In 1942 the corresponding areas were 6900 ha and 2690 ha respectively. Therefore while the total area has increased by 40%, the erosion prone area has increased by 104%.

Fig. 2 previously has shown the deposition trends resulting from the river form analysis. Imposed on this figure is the historic trend in land use in terms of an increase in erosion prone cane land. One would not expect direct correlation because of various influences including the time delay between cause and effect, that is the time taken for eroded soil to become part of the river regime. Nevertheless the general agreement in shape is of interest. This is especially so in relation to the changes measured over the past six years. The sharp increase in the mid-sixties is not reflected in the deposition curves although the time span of measurement (1957-1977) is probably too great. It could well be though that the strong trend in river deposition as shown for nearly all reaches from 1977-83 is a result of the expansion shown from 1976 onwards. If this is so, the general aggradation rate at present may be 3 to 4 times the average rate (1942-1983) which has been principally used in the earlier economic assessment.

The latest published data on measured erosion rates in the Innisfail area are contained in a paper by Prove et al (1984). Table 6 reports the findings for the 1982-83 season which comparatively was a season of low rainfall (580 mm compared with an average of 1 498 mm).

TABLE 6 Measured soil loss for the 1982/83 season (tonnes/hectares)

Site	Cowley	Liverpool Creek	Nerada	Palmerston
Conventional Practices	82	72	74	150
Zero Till	-11	5	6	N.A.
Trash Blanket	-17	-10	5	8

In essence these figures indicate a soil loss of 70 to 150 t/ha/a due to tillage operations. Other findings in North Queensland indicate rates in excess of 300 t/ha/a so that given the low rainfalls experienced in 1982-83, it appears reasonable to adopt an average value of 150 t/ha/a as an estimate of soil loss from the more vulnerable erosion sites. Since 1942 it was concluded previously that an extra 2 800 ha of caneland contributed to the South Johnstone sediment load and that the majority of this area was on the erosion prone steeply sloped basalts or metamorphics. If we adopt the figure of 150 t/ha/a, this represents some 420 000 tones per annum of extra soil loss from farms.

Quantitative estimates for the relative deposition in drainage lines, creeks and rivers in unknown. Certainly they are all significant and yet a large proportion is also likely to be carried through the system to the sea. The extra erosion rate of 420 000 tonnes per annum can be compared with the estimated increase in river deposition of 100 000 tonnes per annum average. From these figures, the measured rate of deposition is reasonable and still provides for significant amounts to be deposited within the catchment or transported to the sea.

In the current situation, there are 5 490 ha of caneland located on the steep basalts and metamorphics. Again using the figure of 150 t/ha/a, the gross erosion may be 823 000 tonnes per annum. A river deposition rate of 100 000 tonnes per annum is obviously feasible and it could be in current circumstances that the higher rate of measurement from 1977 to 1983 of 300 000 tonnes per annum is a reasonable estimate.

CONCLUSIONS

Of some 9 700 ha of caneland in the South Johnstone catchment, 5 490 ha are located in the highly erosion prone areas of steep basalts or steep metamorphics. Soil erosion rates in such areas have been measured at greater than 300 tonnes per hectare per annum. From recent trial results in a drier than average year, an average of 150 tonnes per hectare per annum has been adopted as a conservative estimate. Total current soil loss may therefore be as high as 823 000 tonnes per annum in the catchment.

The average aggradation in the river from 1942 to 1983 is estimated at 100 000 tonnes per annum. Similar evaluation from 1977 to 1983 indicates that the current aggradation may be 3 times that amount, say 300 000 tonnes per annum. If this current rate is valid and not a temporary change induced in the short term by other causes, it probably reflects the significant expansion into erosion prone lands since 1975.

Economic modelling of urban residential and commercial flood damages has been presented for a variety of parameters. Based on a 7% discount rate adopting the average aggradation rate since 1942, additional urban damages due to river aggradation approximate $16 000 per annum for Innisfail and $4 000 per annum for neighbouring urban areas. If the current aggradation is twice that average historic rate, costs are $39 000 per annum and $10 000 per annum respectively. Present worth total values of damages are $290 000 for the 1942-83 rate and $700 000 if the current rate is double that historic rate. Rural flood damages in the basin are not necessarily typical of coastal Queensland but examination of the damage consequences of aggradation indicate an estimate of $23 000 per annum. This represents a present worth value of $330 000.

REFERENCES

Cameron McNamara (1985) Johnstone Rivers system flood management study, Technical Report no. 82-1089, Brisbane, Australia.

Connor, T.B. & Woodhouse, M.P. (1981) A dynamic flow model for two Queensland river deltas. In: Hydraulics in Civil Engineering, (Proc. Sydney Conf. 1981), Institution of Engineers Australia.

Connor, T.B., Fox, I.B. & Woodhouse, M.P. (1982) A rural drainage master plan for the Herbert River canelands, In: Rural Drainage in Northern Australia, (Proc. Toowoomba Symp. Sept. 1982), Darling Downs Institute of Advanced Education.

Connor, T.B., Ahern, P.A., Woodhouse, M.P. & Ford, B.R. (1984) Applications in mathematical flood plain modelling, In: The Engineering Conference, (Proc. Brisbane Conf. April 1984), Institution of Engineers, Australia.

Mullins, J.A., Truong, P.N. and Prove, B.G. (1984) Options for controlling soil loss in canelands - some interim values, Proc. Aust. Soc. Sugar Cane Technologists.

Prove, B.G. et al (1984) A review of results of trials with trash management for soil conservation, Proc. Aust. Soc. Sugar Cane Technologists.