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Land use and water quality trends of the Fitzroy River, Australia

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Abstract Analysis of long-term trends in water quality indicators is critical to an understanding of the cause and effect of environmental change for resources management. The Fitzroy Basin is the second largest catchment in Australia, and one of the largest sources of freshwater and sediment for the Great Barrier Reef (GBR) lagoon. The basin was largely undisturbed prior to the 1960s. At present, about 90% of the basin has been cleared for grazing, cropping, and sown pasture. The paper shows that in spite of the large-scale, rapid land clearing, and an increase in sediment concentration at a given discharge, there are no significant trends in mean annual sediment concentration nor in the sediment discharge into the GBR lagoon. Three factors are identified to have contributed to this: (a) declining rainfall in parts of the basin since the 1970s; (b) high inter-annual variability; and (c) the unpredictable nature of where runoff-generating events occur for large river basins.

Key words land clearing; land use; sediment discharge; water quality trend; Fitzroy, Australia

INTRODUCTION

The Great Barrier Reef (GBR) off the east coast of Australia is of great national and international importance. The Fitzroy Basin, with an area of some 142 570 km^2, is one of the largest catchments discharging water and sediment into the GBR lagoon. The Fitzroy Basin has five major sub-basins, namely, Comet, Dawson, Isaac, Lower Fitzroy and Nogoa (Fig. 1(a)). The mean annual flow amounts to 4.42×10^9 m^3, or 32.6 mm in runoff depth for the period from 1965 to 2008. Given its size, the Fitzroy is quite heterogeneous in terms of runoff and sediment generation, with the Isaac sub-basin, receiving the highest amount of rainfall and generating the highest volume of runoff with the lowest sediment concentrations (Joo *et al.*, 2005).

Flows are highly seasonal with more than 90% of the flow occurring in the wet season of the year in summer and autumn from December to May. The inter-annual flow variability is high, with the standard deviation more than 110% of the mean. The climate is tropical to sub-tropical, with the Tropic of Capricorn almost dividing the basin in half. Rainfall is mostly related to the tropical monsoon, with occasional widespread heavy rainfall from degenerated tropical cyclones from the Coral Sea off the east coast of Queensland.

The Fitzroy Basin is situated almost exclusively in what is known as the Brigalow belt bioregion (Verwey & Wearing, 2007). The Brigalow belt is characterised by Brigalow (*Acacia harpophylla*) forest and other ecosystems such as eucalypt forests, grasslands and riparian communities (Young *et al.*, 1999). Since the late 1950s, the basin has undergone extensive land clearing and land use change, with 4.5 million hectares of Brigalow land cleared between 1962 and 1976 as part of the Brigalow Development Scheme (Donahue, 1984). The impacts of these essentially irreversible changes on the water quality, and the consequential impact on the GBR, have been subjects of extensive research to gain a better understanding of the processes involved, and to develop sustainable management strategies (e.g. Carroll *et al.*, 2012).

Although the effect of changes in land use and management practice on water quality is well understood at the small scale in the region (Carroll *et al.*, 1997; Silburn *et al.*, 2011), the effect of land clearing at the basin scale in terms of the sediment delivery to the GBR lagoon is not well documented. For this paper, we use long-term flow and sediment concentration data as well as estimates of the sediment discharge at the end of the river system to address whether there are any significant changes in flow and sediment delivery of the Fitzroy River to the GBR lagoon, and whether the impact of land use change on water quality is detectable given the size and climate variability of one of the largest river basins in Australia.

DATA AND METHODS

Historical land use data were compiled from different sources. For the period prior to 1961, data were compiled from reports and government publication (Lloyd, 1984; Fensham & Fairfax, 2003). For between 1961 and 1988, data were compiled from reports (e.g. Verwey & Wearing, 2007) and Fensham & Fairfax (2003). Clearing rate was based on interpretation of aerial photography (Fensham & Fairfax, 2003), although their study area in Central Queensland was not entirely in the Fitzroy Basin. Since 1988, satellite imagery was used to update land clearing data on a regular basis as part of the SLATS project funded by the State Government (SLATS, 2010), and provided the most reliable, and detailed information on land clearing in the basin over the past 25 years.

The gauging station for monitoring water and sediment discharge into the GBR lagoon from the Fitzroy is located at The Gap (GS130005A) with a basin area of 135 757 km^2, or 95.2% of the Fitzroy Basin. Estimation of annual sediment loads requires collation of daily flow and sediment data. Water levels were automatically recorded at gauging stations by the Department of Natural Resources and Mines (DNRM). The recording frequency varied from between 10 min during high flows to a few days during dry periods. The water level recordings were converted to discharge using flow rating curves, which may lead to uncertainty of about 10% in discharge (Ray Alford, pers comm.). Data on total suspended sediment (TSS) concentrations have been collected at The Gap gauging station on the lower Fitzroy by DNRM under the Surface Water Ambient Monitoring Network (SWAN) programme since 1973, on an opportunistic basis. These data were combined with additional TSS concentration data collected since 2005 under the Reef Plan's Great Barrier Reef Catchment Loads Monitoring Programme (formerly the GBRI5 programme), which focused on more frequent sampling during high flow events. The samples were collected and analysed according to well-established standards (Polaschek *et al.*, 2007; Joo *et al.*, 2012).

Flow and TSS concentration relationships quantify the expected TSS concentrations for a given flow rate. Considerable variability in TSS concentration can lead to great uncertainty in the estimated sediment discharge (Joo *et al.*, 2005). Variability in TSS concentration can occur as a result of many climatic, land use, and hydrodynamic factors, including, but not limited to, rainfall intensity and duration, antecedent conditions (Wood, 1977; Sichingabula, 1998), supply depletion (Walling & Webb, 1980, 1981; Asselman, 1999; Picouet *et al.*, 2001), different stages of the hydrograph, and variable source areas (Heidel, 1956; Klein, 1984; Joo *et al.*, 2005, 2012). To reduce the variability in TSS concentration at a given flow rate for better estimation of sediment discharge, two sediment rating curves were developed based on the principal source of surface runoff for the lower Fitzroy at The Gap (Joo & Yu, 2011).

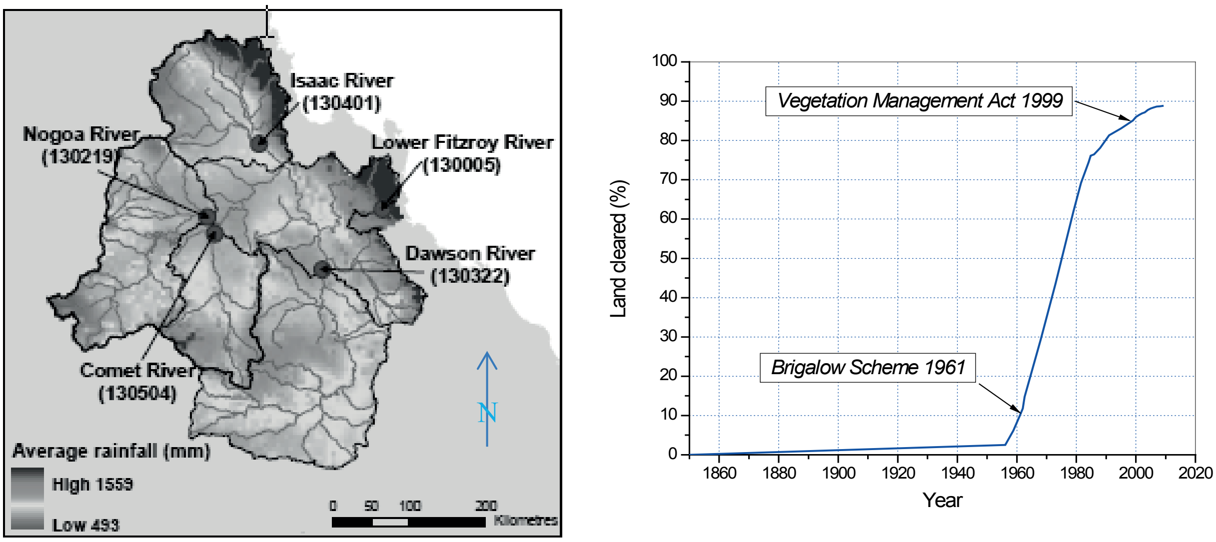

Fig. 1 (a) Location map of the Fitzroy Basin. (b) History of land clearing in the Fitzroy Basin.

The sediment concentration–flow relationships were developed as a power function in the form:

$$C = a\, C_f\, Q^b \qquad (1)$$

where C is TSS concentration, Q is discharge, a and b are regression constants using log-transformed flow and TSS concentration data, and C_f is a correction factor to remove an inherent bias introduced as a result of log-transformation (Ferguson, 1986). The smearing estimate was used to calculate this correction factor (Duan, 1983):

$$C_f = \left(\sum 10^{\varepsilon_i}\right)/\, n \qquad (2)$$

where the summation is over all the measurements; n the sample size, and ε_i is the error term, or the residual, for the ith measurement, i.e.:

$$\varepsilon_i = \log C_i - \left(\log a + b \log Q_i\right) \qquad (3)$$

Daily sediment discharge, Q_s, was calculated as the product of daily discharge and estimated sediment concentration for the day, and these daily values were aggregated to obtain annual totals. Mean annual TSS concentrations were calculated as the ratio of total sediment discharge over total flow volume for the year.

RESULTS

History of land clearing in the Fitzroy Basin

Land clearing in the Fitzroy is best summarised as having three distinct phases. The first phase covers a period of about 100 years from early European settlement in the Fitzroy region to the late 1950s. Land clearing during this period was minimal and localised. Results from Fensham & Fairfax (2003) indicate that about 15% of the land in central Queensland had been cleared by 1961, while Verwey & Wearing (2003) mention that only about 3% of the designated area for the Brigalow Scheme, which accounts for about 30% of the Fitzroy Basin, had been cleared by 1961. Phase II, from 1961 to 1988 represents a period of systematic and intensive land clearing at a rate of about 2.5% per year. Nearly 70% of the basin was cleared over this period. Phase III, since 1988, has seen a marked decline of land clearing in the Fitzroy Basin. SLATS report for 2008–2009 showed an area of 15 270 km^2 was cleared over a period of 21 years between 1988 and 2009, or another 11% of the Fitzroy Basin at a rate of 0.51% per year (SLATS, 2010). Phase III coincides with a period of improved technology for monitoring land use change, and introduction of the Vegetation Management Act in the late 1990s. Figure 1(b) shows a re-constructed history of land clearing in the Fitzroy Basin. It is interesting to note that the scale and the rate of land clearing during Phase II in the Fitzroy Basin were comparable to those in South America (Laurance *et al.*, 2001; Steininger *et al.*, 2001; Fensham & Fairfax, 2003). At present, nearly 90% of the basin has been cleared. Table 1 shows various types of land use as of 2004. It can be seen clearly that, by far, the dominant land use is grazing, natural vegetation and production forestry in relatively natural environments. It is in the context of this rapid land clearing and land use change that the dynamic relationship between flow and sediment concentration and trends in sediment discharge into the GRB lagoon were examined for the second largest river basin in Australia.

Table 1 Land use types in the Fitzroy Basin in 2004 (adapted from Rowland *et al.*, 2006)

Land use types	Area (km^2)	Area (%)
Conservation area with minimal use	7 060	4.95
Grazing and production forestry	124 831	87.56
Dryland agriculture (cropping)	8 013	5.62
Irrigated agriculture (cropping and horticulture)	858	0.60
Intensive use (urban and mining)	1 203	0.84
Water (including wetland)	605	0.43
Total	142 570	100

Relationships between flow and sediment concentration

While large-scale land clearing commenced in the early 1960s, monitoring of TSS concentration and water quality generally did not begin until the mid-1970s. Water quality monitoring continued and intensified in the 2000s with increased concern about the potential impact on the GBR from sediments and nutrients in surface runoff from coastal catchments (Packett *et al.*, 2009; Carroll *et al.*; 2012; Joo *et al.*, 2012).

Figure 2(a) shows the sampling frequency since the 1970s, and it is clear that the sampling rate has tripled since 2000 compared to the three preceding decades. It can also been seen that a large number of samples were taken during flood events as represented by vertical jumps in Fig. 2(a). This increase in sampling frequency would suggest better estimates of the total sediment discharge in recent years. This has implications for inferred changes in water quality over time for the Fitzroy Basin. Figure 2(b) shows the relationship between discharge and TSS concentration. These observations were separated into three non-overlapping groups with about 10 years in record length for each. Regression statistics are presented in Table 2. It is evident that there is a considerable amount of scatter in the relationship between discharge and sediment concentration. At a given flow rate, the sediment concentration can vary by up to two orders of magnitude. Based on regression analysis, for a given flow rate, the sediment concentration for 1998–2008 is systematically higher than the corresponding value for the period of 1973–1986. The slopes of the two regression equations are about the same (~0.3 from Table 2); the intercept differs by 0.42 log unit, or a factor of 2.6 between the two periods, suggesting the sediment concentration at least doubled over a period of about 20 years. The *t*-value for the difference in the intercept is about 2.3, suggesting statistical significance in the sediment concentration for a given flow rate for the Fitzroy River at The Gap.

From a different perspective, changes in the TSS concentration at a given flow rate may be ascertained by examining the residuals, or departures from the regression line using the entire data

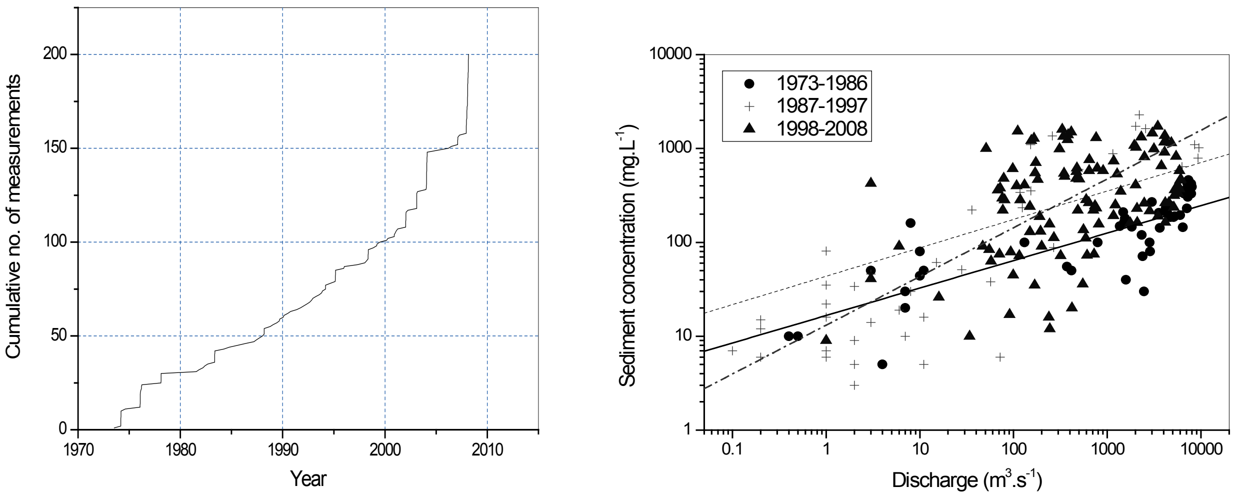

Fig. 2 (a) Cumulative number of TSS concentration measurements at The Gap, Fitzroy River. (b) Flow and TSS concentration relationship at The Gap, Fitzroy River.

Table 2 Relationships between discharge and sediment concentration for different periods in the Fitzroy Basin.

Period	n	log(*a*)	*a*	*b*	C_f	R^2
1973–1986	46	1.22±0.10	16.6	0.295	1.19	0.66
1987–1997	42	1.12±0.10	13.1	0.520	1.58	0.73
1998–2008	112	1.64±0.15	43.5	0.303	1.67	0.23
Overall	200	1.31±0.07	20.9	0.372	1.82	0.48

n – sample size, *a* and *b* as in $C = aQ^b$, C_f – correction factor.

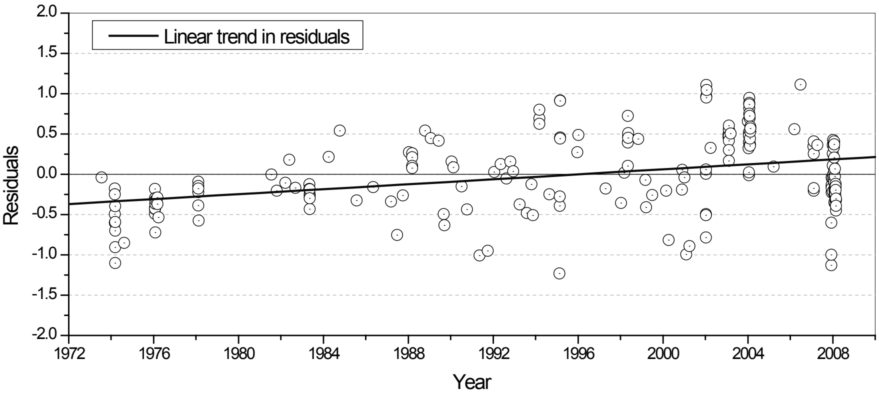

Fig. 3 Residuals for the log-log regression line between discharge and TSS concentration. Positive residuals indicate that observed TSS values exceeded those estimated the regression equation.

set (Table 2). Figure 3 clearly shows a strong and significant (at 0.05 level) increasing trend in the residuals. If we use the regression line for the entire data set, we would tend to over-estimate, i.e. negative residuals during earlier periods, and under-estimate in more recent times.

Trends in flow, sediment discharge and TSS concentration

It is commonly expected that following land clearing, surface runoff and sediment concentration would increase, leading to an increase in sediment discharge over time. The increase in the TSS concentration at a given flow rate reported in the section above in fact supports this notion of increased sediment delivery with land clearing and land use change. However, annual flows, sediment discharge, and flow-weighted mean annual TSS concentrations have so far shown no sign of an increasing trend over the past 44 years (1964–2008) (Table 3 and Fig. 4). Linear regression analysis shows that the flow, sediment discharge and the mean TSS concentration, in fact, have all decreased slightly; Table 3 summarises the magnitude and inter-annual variability of these three variables, and the rate of decrease and the corresponding *t*-statistic, suggesting insignificant changes. It is interesting to note the high variability of the annual flow of the Fitzroy, and the even higher variability for sediment discharge. The trend in flow and sediment discharge varies depending on the time period. If we choose a 30-year period from 1974 to 2003, representing the first 30 years of water quality monitoring in the Fitzroy, a significant decrease in streamflow could be detected (Table 3). It is also worth noting that the rate of change in the mean annual sediment concentration is smaller in percentage terms when compared to that in annual flows. This occurred because of the underlying increase in sediment concentration for a given flow rate for the lower Fitzroy.

Table 3 Time series analysis of annual flow, sediment discharge, and mean annual sediment concentration at The Gap gauging station, the lower Fitzroy River.

	Mean annual	Cv	Trend (% of the mean)	*t*-statistic
Whole period (1965–2008)				
Q (10^9 m^3)	4.42	1.19	–1.2%	–0.85
Qs (10^6 tonnes)	3.26	1.59	–2.4%	–1.26
TSSC (mg L^{-1})	545	0.68	–0.05%	–0.07
30 years (1974–2003 only)				
Q (10^9 m^3)	5.14	1.16	–5.2%	–2.37†
Qs (10^6 tonnes)	3.79	1.43	–6.1%	–2.15†
TSSC (mg L^{-1})	593	0.61	–0.17%	–0.13

(Q – annual flow; Qs – annual sediment discharge; TSSC – mean annual suspended sediment concentration; Cv – coefficient of variation; † – significant at 0.05 level).

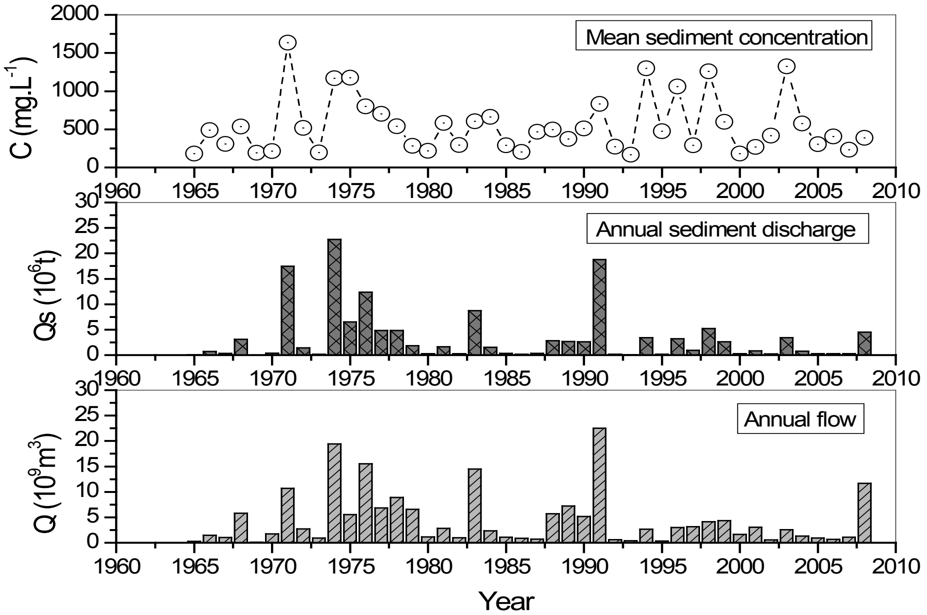

Fig. 4 Time series of flow, sediment discharge, and mean annual sediment concentration at The Gap over the past 44 years (1965–2008).

Detecting change – a discussion

Analysing and detecting long-term trends in water quality indicators are critical to an in-depth understanding of the cause and effect of environmental change for better resources management. Changes in water quantity and quality, whether they are results of climate or land use changes, or some combinations of the two, are of intrinsic interest to hydrologists, resource managers and policy makers. We began this research assuming that a significant upward trend in sediment discharge into the GRB lagoon would be unmistakeably obvious, with ramifications for the elevated impact on the coastal environment. To the contrary, in spite of the dramatic and rapid land clearing in the basin, and some evidence to suggest an increased sediment concentration at a given flow rate, we could not find an increasing trend in sediment discharge into the GBR lagoon with any useful level of statistical significance. Here we offer three plausible reasons for this apparent contradiction.

The first reason is related to recent rainfall variation in the region. Extensive analysis by the Australian Bureau of Meteorology (www.bom.gov.au) shows that rainfall since 1970 has decreased in some parts of the Fitzroy Basin, and by up to 5 mm/year in the northwestern and eastern parts of the basin. The trend in rainfall is not nearly as clear if we include the data from the 1960s. Since 1960, in fact, much of the wettest part of the Fitzroy Basin, i.e. the headwater region of the Isaac sub-basin, has shown an increasing trend in rainfall. We can argue that if we had received, in more recent years, high rainfall and streamflow like those in the 1970s, we might have experienced significantly higher sediment discharge into the GBR lagoon.

Secondly, temporal trends in sediment discharge can occur as a result of a combination of where runoff occurs, and where the sediment concentration is expected to be high for a given runoff rate. At the small scale where rainfall is essentially uniform in space, trends in sediment discharge mainly depend on the trend and variability in the sediment concentration, which is largely related to the soil, vegetation cover, and land use and management practice under consideration. However, in large basins where rainfall is not uniformly distributed (and often it occurs in isolated parts of the basin), spatial variability in terms of cover and other surface characteristics can magnify the observed variability in TSS concentration and sediment discharge at the end of large river systems like the Fitzroy (Packett *et al.*, 2009; Joo & Yu, 2011). For such basins, climatic variability and mixing of runoffs from different source areas can mask land-related signals at the end of the river system. Therefore, to assess the impact of land-related changes on delivery of sediment and nutrients to the coastal environment from large river basins, identifying different runoff source areas and separating the effect of climatic variability from land use effects is absolutely essential.

Finally, from a statistical perspective, there is a limit to change detectability if the underlying processes are highly variable in time and space. To further illustrate this point, we have derived an expression for the magnitude of change that can be regarded as significant, given the underlying variability as measured by the coefficient of variation, i.e. the ratio of standard deviation over the mean. The following assumptions were made: (a) two contrasting periods of equal length; (b) the coefficient of variation is identical for both periods; and (c) the *t*-test for independent samples with unequal variance applies. Many Australian river flows have the highest natural variability in the world (Peel *et al.*, 2004). Annual flows of the Fitzroy have a Cv value of 1.19, possibly one of the highest in the world for basins of this size (Table 3). To illustrate the effect of variability on change detectability, Fig. 5 shows the amount of increase that would be required for the increase to be significant for a given level of variability. For instance, if the coefficient of variation equals 1, the mean flow of a 10-year period has to be some 40% higher than that for another 10-year period before the increase can be regarded as significant at the 0.05 level. If the record length is 30 years for each of the two periods, the difference needs to be at least 13% to be significant.

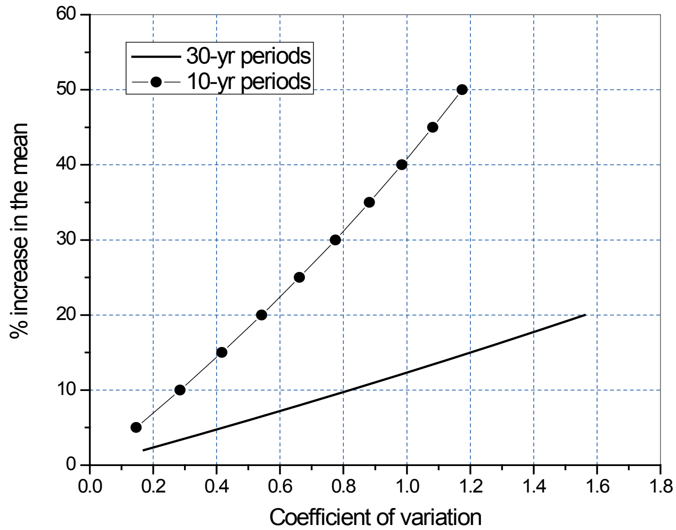

Fig. 5 Significant increase (1-tail at 0.05) as a function of the coefficient of variation and record length.

CONCLUSION

It is well documented that nearly 70% of the Fitzroy Basin was cleared for development in the 1960s and 1970s, and the rate of clearing then decreased from the mid-1980s. Associated with the land clearing and land use change, there is evidence to indicate that along the lower Fitzroy River, the total suspended sediment concentration has significantly increased in recent years at a given flow rate. However, annual freshwater and sediment discharge to the Great Barrier Reef lagoon has not significantly increased since the mid-1960s. In fact, flow and sediment discharge have decreased, and decreased significantly for certain 30-year periods. This apparent contradiction can be attributed to recent decrease in rainfall in parts of the basin, the variable runoff-generating area, and the high natural variability of the flow which limits change detectability.

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