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Ecological and Economic Analysis of Watershed Protection in Eastern Madagascar

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Watershed protection is one of the many goods and services provided by the world's fast disappearing tropical forests. Among the variety of watershed protection benefits, flood damage alleviation is crucial, particularly in upland watersheds. This study is a rare attempt to estimate flooding alleviation benefits, resulting from the protection of upland forests in Eastern Madagascar. A three stage model is used to examine the relationship between the economic concept of value and the bio-physical dimensions of the protected area. This approach combines techniques from remote sensing, soil and hydrologic sciences and economics. In stage one, the relationship between changes in land use practices and the extent of flooding in immediate downstream is established by using remotely sensed and hydrologic-runoff data. Stage two relates the impact of increased flooding to crop production by comparing the hydrologic data with the agronomic flood damage reports for the same time period. In stage three, a productivity analysis approach is adopted to evaluate flood damage in terms of lost producer surplus. The presence of the Mantadia National Park, in eastern Madagascar, is designed to prevent land conversions and changes in hydrologic patterns, thereby alleviating flood damage. This averted flood damage is a measure of the watershed protection benefits to society. Given that natural systems are subject to considerable stochastic shocks, sensitivity analysis is used to examine the uncertainty associated with the key random variables. The results of this analysis should help policy makers assess trade-offs between the costs and benefits of protecting tropical rainforest.

Keywords: protected areas, watershed protection, tropical rain forests, Madagascar, deforestation, flooding, stormflow, crop losses, economic evaluation, productivity analysis, forest valuation.

1. Introduction

Forests in many areas of the world are vanishing at a rapid rate. The annual deforestation rate in the tropics has increased from 0·6% in the 1980s to 1·2% in the 1990s. This

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figure is higher for Africa at 1·7% (Dembner, 1991). A large number of developing countries experiencing increasing deforestation trends are also facing acute shortages of fuelwood, fodder, industrial timber and other forest products for domestic use. Besides potential environmental degradation, depletion of forests and trees may exacerbate poverty, displace indigenous populations and impede agricultural productivity. Deforestation, especially in the humid tropics, has serious regional and global implications. Among those that have caught the attention of the world at large are potential climate change, loss of biodiversity and degradation of large watersheds. While acknowledging the importance of biodiversity conservation and global climate regulation as issues of paramount concern, this paper focuses on watershed protection—its ecological and economic aspects in the watershed of the Vohitra River in Eastern Madagascar (for a more comprehensive evaluation see Kramer *et al.*, 1994).

Though watershed protection offers a variety of benefits, this study concentrates on flood alleviation. Watershed protection, as provided by forest cover, has a strong bearing on floods because forests have a strong impact on the dynamics of floods. This impact involves two processes: regulating the rate at which water moves into streams, and regulating total water runoff (Richter *et al.*, 1992). It is generally believed that deforestation increases the frequency and severity of floods, yet there is limited empirical work to demonstrate these effects, especially in the tropics (Courtney, 1981). An example study in a temperate setting was based on a sample of catchments in England. This study showed that forest soils were several times as permeable to rainfall as were pasture soils (Clark, 1987). Pasture catchments had five times the discharges of forest catchments for 50-year floods. A larger scale analysis, studying the deforestation in the upper Amazon basin, hypothesized a significant increase in the annual crest of the Amazon over a time period in which extensive deforestation took place (Gentry and Lopez-Parodi, 1980). This result has been refuted by Richey *et al.* (1989) who reconstructed an 83-year record for the basin and showed that there had been no statistically significant change in discharge over the period for which there were records (1903–1985).

Clearly, it is important not to overstate the case. While forest hydrologists have accepted that forest cutting results in higher yields of streamflow (Bosch and Hewlett, 1982), there has been no similar consensus on a cause–effect relationship between forest cutting in the headwaters and floods in the *lower* basin (Hewlett, 1982). Although flooding may increase close to the area cut, as water is routed down a major river basin, this effect becomes less significant amid other important factors such as intensity and total volume of precipitation, the direction in which this precipitation moves across the basin, and the size and morphometry of the basin (Hamilton, 1988). The local soil and climatic characteristics and the nature of land use that follow forest removal are important influences on the intensity of flooding (Bruijnzeel, 1990). Yet, an increase in stormflow and peakflow magnitude cannot be avoided, even with careful land use (Hsia, 1987). Thus, if there is agriculture activity in lands in the vicinity of the forest cutting, floods can cause significant economic losses due to the destruction of crops.

There is mounting concern, supported by anecdotal evidence, that increasing rates of deforestation are causing greater flooding in the eastern half of the island of Madagascar where the monsoon rains are particularly severe. The island is subject to wet-season flooding and cyclones in February and March (Richter *et al.*, 1992). Periodically, these floods damage agricultural crops, especially those located in alluvial plains along streams and rivers (Donque, 1971). Major floods occurred in eastern Madagascar in 1959, 1972 and 1986, while many small watersheds have been flooded frequently in other years. The catastrophic floods in 1959 were extremely destructive and were graphically described in the Journal, *Revue Bois Forets de Tropiques* (Saboureau, 1959). In addition, research conducted in the Mantadia area shows evidence of increased runoff in watersheds cleared for swidden agriculture. If current rates of deforestation continue, flooding may increase further and cause greater economic losses. In light of the fact that deforestation effects are likely to be local, the economic aspects of this analysis will focus only on local effects.

The watershed of the Vohitra river contains the Mantadia National Park (see Figure 1), an area of 26 787 hectares established in 1989 as an outcome of Madagascar's National Environmental Action Plan (World Bank, 1988). To the extent that the Mantadia National Park and other aspects of the Environmental Action Plan reduce deforestation, one benefit of these conservation activities will be flood prevention. Establishment of protected areas provides a variety of benefits, including watershed protection (Dixon *et al.*, 1990). However, empirical studies of this ecological service are rare. The purpose of this study is to fill this gap and estimate the economic benefits of reduced flooding that may arise from the establishment of the Manadia National Park. This exploratory study is an example of the combination of ecological and economic information to better understand interactions between humans and a rapidly changing environmental system.

2. Overview of methods

By means of a productivity analysis, we measured the benefits (in terms of increased economic welfare) to farmers in the Mantadia region of the Vohitra River watershed. These benefits resulted from reduced flooding as a consequence of reduced deforestation which, in turn, results from the establishment of the park and buffer zone. Productivity analysis is a valuation method suitable for examining the effects of environmental quality on products which enter into market transactions. This approach has been used in the past to value the effects of various types of environmental change on agriculture, forests and fisheries (Freeman, 1979).

We used a three stage model (Freeman, 1993), shown in the diagram below, to examine the relationship between the economic concept of value and the physical and biological dimensions of the resource system being valued. The particular application to flooding is a variation of the approach proposed in FAO guidelines on watershed management (Gregersen *et al.*, 1987). In our study, the first set of functional relationships, $F = F(d)$, relates some measure of environmental quality (extent of flooding) to human interventions (land use practices, particularly deforestation) that affect it. The second set of relationships, $Y = Y(F)$, involves the human uses of the environment (agricultural production) and their dependence on environmental quality (intensity of flooding). The third set, $V = V(Y)$, measures the change in economic welfare because of a change in use of the environment (loss in producer surplus).

For Stage I, described in Section 3 of this article, the analysis proceeded by examining the history of deforestation in the Mantadia area using remotely sensed data. Aerial photos taken in 1957 and satellite images recorded in 1976 and 1984 were combined with topographic information to describe the deforestation history of the area (Green, 1993). These deforestation rates, which quantify the changing land uses, were combined with information on floods to estimate a structure of flooding patterns, particularly the growth in intensity and frequency of floods of various magnitudes. The relationship between deforestation and flooding was examined using two different data sets: one

Deforestation

Stage I: $F = F(d)$ ↓

Changes in flooding patterns

Stage II: $Y = Y(F)$ ↓

Agricultural production loss

Stage III: $V = V(Y)$ ↓

Loss in producer surplus

based on a set of monitored small watersheds in the Mantadia area and one based on long term weather data and flow rates of the Vohitra River.

For Stage II, described in Section 4 of this article, the predicted changes in flooding patterns were used to predict changes in area inundated and the associated changes in damage of paddy production in the immediate downstream. Based on local interviews and regional data on flood destruction, we fitted a logarithmic function to describe these relationships.

For Stage III, described in Section 5 of this article, this change in production was valued at the market price, net of production costs, after making some simplifying assumptions about the form of the market supply and demand curves. Finally, in Section 6, a sensitivity analysis was conducted to determine how the results would vary when some of the key stochastic parameters, such as deforestation rate, are changed.

The entire analysis can be interpreted in a "with and without park" framework. Creation of the park prevents deforestation and thereby results in a mitigation of flooding. Therefore, the true "with-park" scenario is one in which the changes in flooding patterns, resulting from accelerated deforestation, do not happen. In the "without park" case, the flooding damage would amount to a sizeable economic loss. In the "with park" case, these losses are considerably diminished. Thus, any estimation of the benefits of the park creation must include this loss prevention.

3. The relationship between deforestation and flooding: $F = F(d)$

Remote sensing was used to construct a deforestation history of the study area (Green, 1993). The technique made use of (1) 1:50 000 scale topographic maps and (2) 1: 1 000 000 scale negatives of Landsat satellite images. The eight topographic maps encompass an area roughly 88 km (N–S) by 63 km (E–W), a total of approximately 550 000 ha which includes the entire watershed of the Vohitra River. Forest cover was depicted on the topographic maps by overlaying information from the 1:50 000 scale aerial photographs acquired in 1957 (based on a photo interpretation). These overlays

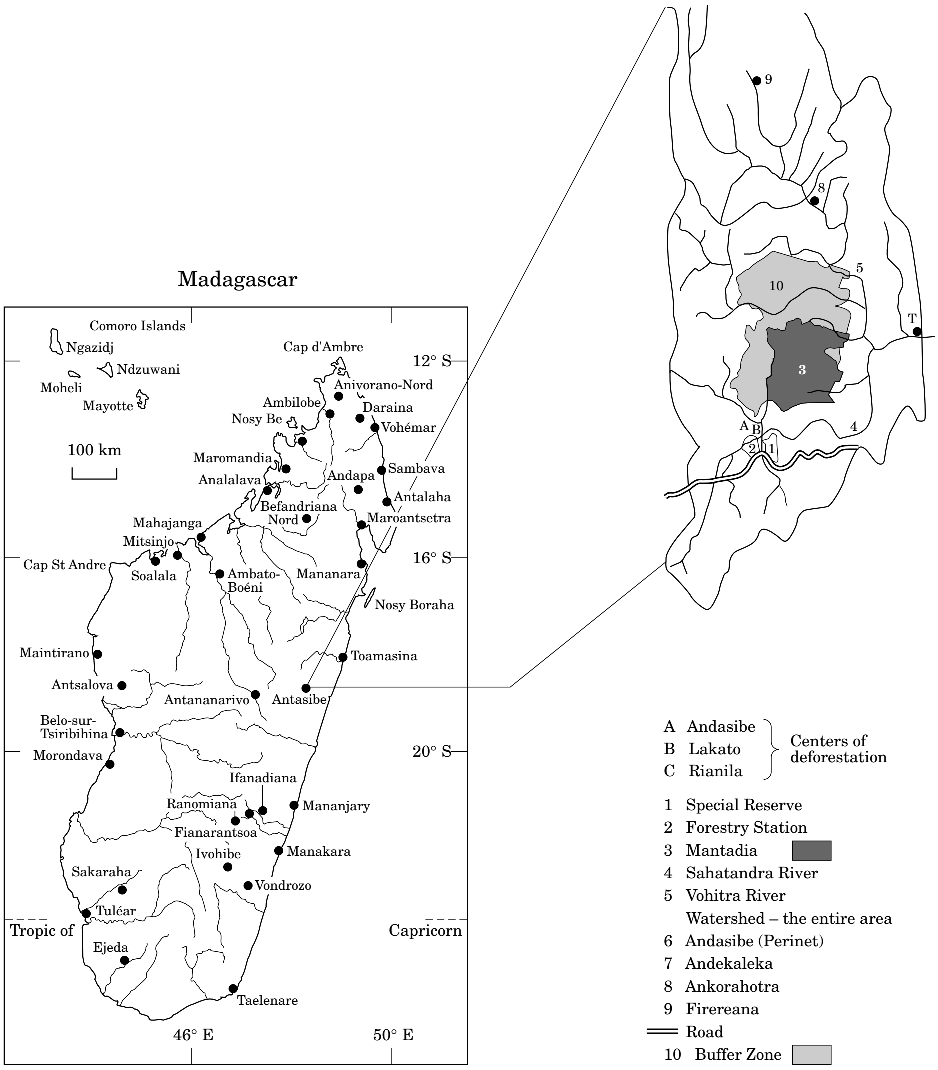

Figure 1. Mantadia National Park in Vohitra Watershed (Eastern Madagascar).

formed the base maps of the forest extent in 1957, upon which subsequent information about the changes in forest cover from the Landsat images of 1976 and 1984 were overlaid (Green, 1993). Thus, this multiple overlaying estimated the chronology of deforestation. From these maps it was possible to examine the impact of topography, slope and elevation in particular on deforestation in this area.

Deforestation has proceeded generally from areas of low to high elevation, with forest clearing happening faster through terrain of low and moderate slope, and becoming stabilized in areas of high relief (most notably along the eastern escarpment of the plateau). While deforestation between 1976 and 1984 virtually eliminated all large tracts of lowland forest in the study area, forests of the plateau experienced little cutting up to 1984. Deforestation in this region has already isolated the forests of a Special Reserve and a Forestry Station and has penetrated into the south-west and south-east corners of Mantadia Park. Steep slopes within Mantadia will probably limit deforestation in the south-west and along the north-west portions of the park, yet forests present on the relatively flat land that remains in the south-east portion of the Park may be threatened with clearing. The park area has an elevation of 800–1200 meters and a range of slope from 0–12 degrees. Using the figures reported by Green (1993) for the change in forest cover, we have ascertained an annual deforestation rate of 2·17% for the park area (Appendix 1). Given this rate, in a "without park" scenario, the protected area (park plus buffer), which lies in the above elevation and slope range, will lose all its forest cover in approximately 46 years.

The specific way that a forest regulates floods depends upon the watershed's weather and climate, soil, plants, topography, drainage channel characteristics and land use. The role of forests in controlling floods should therefore be examined on a site-specific basis. Although these topics have been under scientific investigation for about a century, there is a great need to understand better the relationships of forests and floods in the upland regions of the tropics (Richter *et al.*, 1985). Whether these forest conversions have had a detectable impact on flooding is an important element of this study. We first reviewed specific hydrologic experiments conducted on the Perinet Experimental Watersheds which lie within this river basin. Second, we analysed long-term discharge data from the Vohitra River to examine whether trends in increased flooding could be detected in recent years (Richter *et al.*, 1992).

Since the early 1960s, small watershed studies near Perinet have tested effects of land uses on flooding. Land uses studied included primary forest, secondary forest, traditional rice agriculture with burning (swidden), and agriculture with terraces and other conservation practices. Detailed watershed studies by Bailly *et al.* (1973) and Sarrailh and Rakotomanana (1978) quantify how conversion of primary forest to agricultural uses and secondary forest affects flood dynamics in these small highland watersheds.

An eight-year experiment at the Perinet Experimental Watersheds suggests that flooding differs quite considerably between primary and secondary forest. Stormflow from a 30 hectare secondary forest watershed was about *three-fold* more in water volume than from a similar sized primary forest catchment. There are several reasons why there might be increased stream flow from secondary forests, such as reduced infiltration capacity due to soil compaction, decreased evapotranspiration and less extensive rooting. The length of time during which a secondary forest may re-acquire the hydrologic attributes of a primary forest was not reported in Bailly *et al.* (1973) or in Sarrailh and Rakotomanana (1978).

Two agricultural land uses were compared with secondary forests in their effects on flooding in a nine-year experiment at Perinet. Substantially greater volumes of stormflow were produced when secondary forest watersheds were converted to swidden or to conservation farming. Year-to-year variation was substantial but, on average, swidden produced about 154% more stormflow than secondary forest, whereas the carefully cultivated catchment produced 58% more runoff than secondary forests. Although forest conversion to agricultural uses increased rate and volume of all floodwater over the nine-year period, land use appears to have its greatest effects on small and medium sized floods. The physical limits to increased flooding in the secondary forest catchments were apparently approached by this large rainfall event. In Appendix 3 (note 1) we have quantified this differential impact of land use practices on floods of differing magnitudes.

In addition to an examination of the above experiment studies, we were able to

TABLE 1. Time trend statistics resulting from time series data for the monthly discharge of the Vohitra river (1953–1979)

Time trend	Kendall statistic	Tau probability	Sen slope statistic
Maximum monthly discharge	−0·240	0·090	−0·0064
Monthly discharge	−0·057	0·574	−0·0015

analyse discharge data for the Vohitra River at Andakaleka. A 27-year record of monthly discharge (1953–1979) was analysed for flood frequency and time-trend, and, thus, we obtained a second perspective on the problem of flooding in the area. The primary objective of these Vohitra data analyses was to determine whether peak discharges have increased in the Vohitra River over the most recent three decade record. Two time-series of river discharge data were used to address this objective: the series of annual maximum monthly discharges ($N=27$, 1953–1979) and the complete series of monthly discharges over the same period ($N=285$).

Variation in precipitation was removed from each time series so that trends could be examined that were free of variations in precipitation inputs. Monthly rainfall data for this 27-year period were taken from three weather stations in Eastern Madagascar: Antananarivo, Andekaleka and Tamatave. An arithmetic mean monthly rainfall was estimated from the three stations for use in the rainfall–runoff regression model. Log transformed monthly precipitation and monthly discharge were used in the two regression analyses to predict discharge from precipitation. Residuals (observed minus predicted discharge) were determined for the two equations and were plotted against time. These residuals data were considered as the time series of river discharges with variation due to rainfall removed. As it was observed that residuals tend toward zero throughout the time series, it was concluded that, as of 1979, there was no evidence to suggest that flooding of the Vohitra River increased in flood frequency or severity. Specifically, the probabilities of increasing flood flows were not significant at the 0·05 level as tested by the Kendall and Sen slope statistics. This is evident from Table 1.

Several important caveats are in order. First, the time series tested was from 1952–1979; this series could potentially be extended to allow for more recent acceleration of deforestation activities, provided that the complete Vohitra River discharge data could be obtained (1952–present). Despite several attempts, we were unable to obtain data for the more recent years. Second, the fact that we have been unable to detect a trend leads to one of two conclusions: either no trend in flooding existed prior to 1979 (i.e. forest conversion of the river basin had not yet affected flooding) or alternatively, no trend was detectable with the monthly data sets used in this analysis. Our hydrologic results apply to the first increment of time that was examined in the land use investigation (1957–1976) and not to the time of increasing rates of forest conversion that were found in the late 1970s and first half of the 1980s. A more definitive statement might be made about the Vohitra River basin if more detailed daily river data were available that stretched over the entire record (1952–present).

Flooding generally becomes more frequent and more destructive as a result of converting forests to other uses. This potential is amply demonstrated by the studies of forests clearing at the Perinet Experimental Watersheds. In apparent contrast, our analysis of the flooding data from the large Vohitra River basin indicated no increasing

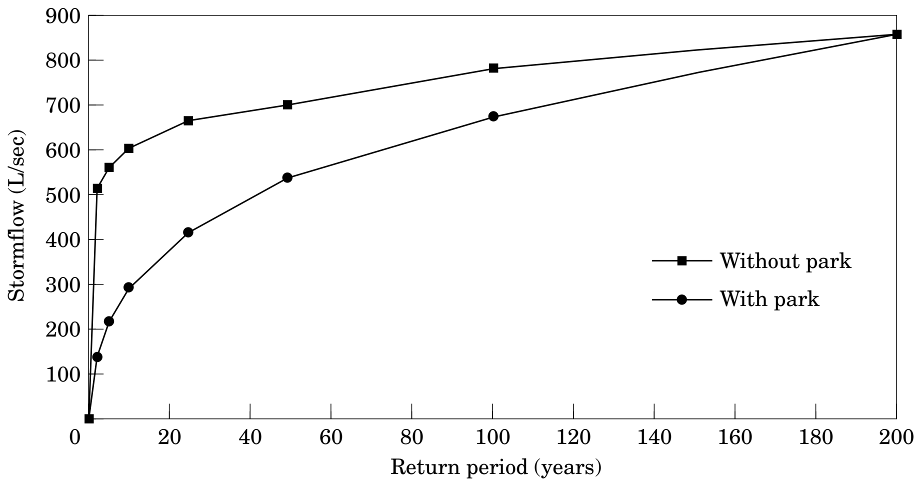

Figure 2. With/without park changes in stormflow.

trend in stormflow over the period 1952–1979. These results, however, should be carefully interpreted.

The 27-year record on which we have concentrated appears to have a distribution of monthly rainfall events that is comparable to hydrologic conditions that have existed over the last century. Thus, using these records the Pearson III distribution method was employed to estimate frequencies of floods of different magnitudes (Appendix 2). These estimates relate stormflow to 2, 5, 10, 25, 50, 100 and 200-year flood events. Using the results from the experiments in the Perinet Watershed and the rates of deforestation, described earlier, it is possible to predict an increase in the stormflow effect in the major streams of the Vohitra watershed (Appendices 3 and 4 (1)). Moreover, since land use has differential effects on floods of different intensities, i.e. forests are able to control small and medium sized floods most effectively, we fitted a diminishing function on flooding intensities as measured in stormflow units of litres/second. For example, as shown in Figure 2 which represents the with and without park effects on stormflow, it was estimated that an annual flood will be 3·8 times as intense at the end of the 46 year period, while the centennial and bi-centennial floods (ones that occur every 100 or 200 years) were not affected (Appendix 3).

Thus, in Stage I, we have quantified the effects of land conversion (human action) on flooding (environmental quality). As seen in Appendix 2, the Pearson III distribution method was used on the 27-year record of the Vohitra River discharge to estimate frequencies of floods of different magnitudes. Further, at an annual deforestation rate of 2·17%, and over a time span of 46 years, the stormflow for the smallest floods is likely to increase by a factor of 3·8 times. Floods with different return periods will register differing "stormflow effects" (Appendix 3, note 2).

This complete magnification will be realized in 46 years. To understand how this increase happens on a year to year basis, we estimated an annual growth in magnification of stormflow (Appendix 3, note 2). This growth rate of the stormflow volume corresponds to deforestation rates as forests are gradually converted for swidden agriculture. These

TABLE 2. Calculation of the extent of flood-related agricultural damage from deforestation of the park area

Return period	Conditional probability of damage	% of crops damaged in floodplain	annual growth in damage	1st year expected*** loss with growth** ($)	1st year expected*** loss with no growth* ($)
2	0·344	13·1	0·030	13 360	12 971
5	0·167	30·4	0·021	15 366	15 050
10	0·093	43·5	0·016	12 185	11 993
25	0·039	60·8	0·010	7100	7030
50	0·020	73·8	0·006	4402	4376
100	0·010	100	0·000	2965	2965
200	0·005	100	0·000	1482	1482

* This is when forests are not converted and there is no corresponding increase in volume of stormflow associated with each flood event.

** Under this scenario, forests are converted (not protected) and the stormflow volume associated with each flood event increases at a rate corresponding to the deforestation rate.

*** These values have incorporated the probability of occurrence of the flood event.

growth rates range from 0·03 for the 2-year flood to 0 (no growth) for the 100 and 200-year floods as shown in Table 2.

4. Estimation of flooding effects on agricultural yields: $Y = Y(F)$

In Stage II, to examine the link between environmental quality (pattern and extent of flooding) and effects on human use (agricultural production loss) it is necessary to account for several parameters that enable estimation of flood damage in the immediate downstream of Vohitra River (United Nations, 1991). These parameters are area of inundation, depth, duration, seasonality and frequency.

Rice, the principal crop that grows in the valley bottoms, lies in the inundated area and is damaged by submersion and the force of water over-spilling the river banks. At the time of the study, rice-paddy destruction in the Mantadia area was not extensive according to local experts (Ferraro, pers. comm.). Many of the hillsides are still under at least some forest cover and many people are able to harvest some of their rice before the heavy rains at the end of the rainy season. Floods primarily affect the paddy, as opposed to swidden rice, which is grown on hill sides. Therefore, we focus on the rice that is in paddy. Also, because floods occur in the rainy season of February and March, by which time some of the paddy is already harvested, yield damage is restricted.

Regional studies and expert opinion provided data on the range and destructive capacity of the two smaller (2 and 5-year) floods (Ferraro, pers. comm.; Rasolofoharinoro, 1988). The assumption was made that the 100 and 200-year floods will damage all the paddy in the effective flood plain, an area of about 650 hectares. For the floods of intermediate magnitudes, a logarithmic function was fitted that used the above information (Appendix 4, note 2). This functional form incorporates the depth, duration and area inundated, as well as a scale factor. The logarithmic nature of the function indicates that the destructive potential of the floods increases, but at a decreasing rate, over a range of increasing flood magnitudes. This is evident in Table 2 in which we see that, while there is a doubling of effective floodplain for the 5-year

TABLE 3. Net present values of agricultural yield losses over the life of the park and across floods of all intensity

	Net present value of Year 1 Total Expected Loss ($)	Aggregate net present value of Total Expected Loss over 46 years ($)
Without park	51 690	678 390
With park	50 790	551 690

as opposed to the 2-year flood, this ratio is as low as 1·2 for a 100-year as opposed to the 50-year flood.

Moreover, we assume that because agricultural yield loss is proportional to the amount of stormflow, the rate of growth of loss is proportional to the growth in the amount of stormflow. The next section estimates the change in economic welfare for the farmers in the vicinity of Mantadia as a result of this loss of agricultural yield.

5. Economic evaluation of agricultural yield losses: $V = V(Y)$

In this third, and last, stage of our approach, we determine the economic impact of the change in environmental quality on human welfare. Increased flooding implies a loss in producer surplus which represents a change in economic welfare. In this case, two simplifying assumptions were made to determine the net market value of the paddy damaged. First, eastern Malagasy farmers were assumed to be price takers, in that they face a perfectly elastic demand curve and have no influence on the farm-gate price for paddy. Given, the size of the "effective flood plain", as opposed to the area that contributes to the determination of the market price, this assumption is valid. Second, we assumed that the supply curve was relatively inelastic; the farmers will decide on how much paddy to plant irrespective of fluctuations in market price. Again, given the subsistence nature of this economy, this assumption is reasonable. In this sense, the farm-gate price can be considered as a shadow price for the paddy. This implies that the monetary value of the loss in producer surplus is estimated using an average price, net of production costs. In the absence of detailed information on demand and supply price elasticity the use of average prices is a reasonable approximation (Maler, 1990).

In estimating frequency of the occurrence of a flood damage of a given magnitude, a conditional probability of damage, and not simply a probability of occurrence, was used. For example, in Table 2 we noted that for a two-year flood this probability was 0·334 and not 0·5 (once every two years). This is because the probability of damage figure must account for the fact that none of the larger floods occur (Appendix 4: note 3).

Thus, aggregate economic welfare is a function of five key variables: (a) the producer surplus per hectare, (b) the effective flood plain, which is the number of hectares damaged by each different flood event, (c) the annual rate of growth of this damage (that corresponds to the rate of increase in stormflow volume) (d) the probability of occurrence for each flood event, and (e) the discount rate. The average annual net return on a hectare of paddy is $453 (Appendix 5). Using this figure, a discount rate of 10%, an exchange rate of 1110 fmg/$ and the information in Table 2, we see that the first year total (across floods of all magnitudes) expected loss is $51 691. As the stormflow volume increases and the associated loss of agriculture yields increases over a period of 46 years, the net present value of the aggregate expected loss amounts to \$678 390. These numbers are relevant for the "without park" scenario where there is no watershed protection.

To estimate the change in economic welfare we turn to the "with and without-park" framework. The establishment of the protected area is expected to prevent deforestation in the 26 787 hectares covered by the park and the buffer zone area. The effect of this on flooding, and thereby on crop damage, will be realized through the elimination of growth in the volume of stormflow. In other words, once the park and buffer area are protected, the floods will not grow in intensity and range, because forests will not be converted for swidden rice production. This "with park" scenario does not imply that floods will not occur and that there will be no loss to crops; rather that the crop losses will be lower because the floods do not increase in their potential to cause damage. Opposite to this, under the "without park" scenario, because forests are converted to other less conservation-based land uses, the magnification of stormflow volume occurs and the ability of floods to cause damage increases. The first year and the aggregate (over the 46 years) expected total loss amounts for both scenarios are reported in Table 3. Thus, for the "with and without-park" comparison, the presence of the park gives society a saving of \$126 700. This amount is simply the difference between the aggregate total expected loss associated "without and with-park" (or "with and without-growth in damage intensities of the floods") scenarios. This difference is therefore the monetary values of the watershed protection benefits of the park.

6. Sensitivity analysis

Our analysis is applied to a natural system subject to considerable stochastic shocks from weather and other natural factors. Furthermore, projecting land use changes into the future adds an additional element of uncertainty. In order to introduce uncertainty in a systematic way into our analysis, we used sensitivity analysis. In project assessments, sensitivity analysis is a useful means to consider the impacts of uncertainty, particularly when there is insufficient information to estimate probability distributions of key variables (Kramer, 1994).

The sensitivity analysis is conducted for the following six variables. The reasons why these variables may be susceptible to fluctuations are briefly explained:

(i) *Deforestation rate*: increases in population growth and poverty may increase the demand for both the trees and the land, and thus cause an increase in deforestation rate. We considered the effect of a rate of 2·5% per annum, instead of the 2·17% rate that we estimated previously.

(ii) *Decrease in amount of stormflow*: the main analysis extended the results of the 30-hectare catchment to the watershed. Therefore, there is a possibility of a scaling error. We tested for a 10% lowering of the stormflow effect.

(iii) *Percent of land in paddy*: we assumed that the Malagasy farmers of Mantadia have a reasonably inelastic supply of rice production. However, if the economy grew significantly and the farmers were able to substitute the amount of paddy production for some other crop less susceptible to flood damage, the aggregate net benefit figure would change. Our analysis tested for a 10% reduction in area used for paddy production.

(iv) *Net returns per hectare*: our estimate of agricultural returns depends on the prices of farm tools, labor and rice. Instead of testing for a change in each of these prices,

TABLE 4. Results from the Sensitivity Analysis

Parameters	% Change in aggregate net watershed benefits of park
15% increase in the deforestation rate	+13·6
10% decrease (scaling down) of the volume of stormflow due to changing land use	−12·3
10% decrease in the paddy production area	−10·0
5% increase in farm-gate price for rice	+6·7
5% increase in wage rate	−1·6
70% decrease in exchange rate	−41·6
50% increase in discount rate	−51·8

we considered (a) a 5% increase in the wage rate and (b) a 5% increase in the rice farm-gate price.

(v) *Exchange rate*: this rate is susceptible to changes in international trade, fiscal and monetary policies. The analysis tested for an approximately 70% increase in the exchange rate from 1110–1900 fmg/$, which is another rate commonly used by analysts.

(vi) *Discount rate*: the 10% discount rate used is one that is often used by multnational aid agencies. However, if it is the benefits to the local people that are of policy interest, then they are likely to have higher discount rates, due to their poverty status. We tested for a 15% discount rate.

The results of the analysis are reported in Table 4. The direction of change in the value of watershed protection benefits, because of a change in the parameter values, was as expected for each case. None of the parameters allowed to vary in the sensitivity analysis caused an unexpected degree of variation in net watershed benefits.

7. Discussion

Our main finding was that the net present value of watershed protection benefits was $126 700. This dollar value represents the benefits from alleviation of flood damage caused by protecting the watershed by establishing the Mantadia National Park. While this may appear to the western reader as a modest benefit, it is important to put this figure in perspective. As one of the poorest countries of the world, in 1991 Madagascar had per capita GNP of $207 (World Resources Institute, 1994–1995). Hence, these benefits would represent a significant economic gain for the region. As stated earlier, watershed protection also implies additional benefits such as prevention of soil erosion and irrigation canal sedimentation which have not been estimated in our analysis.

The Vohitra River is part of a larger river basin which flows eastward to the Indian Ocean. As the topography flattens to the east, there is more irrigated area. This area can also be affected by upstream watershed degradation which can cause increased sedimentation. A recent report on irrigation investments in Madagascar considered the effects of watershed degradation on downstream irrigation systems (Metzel and Baird, 1990). The report asserts that in the east, continued watershed degradation will cause 10% of the irrigated area to suffer yield declines of 25% due to poor water control and the effects of sand deposits, and 2% of the land will be taken out of production due to heavy sedimentation. In addition to these downstream silting effects, investigations by

Malagasy soil scientists and hydrologists suggest that conversion of secondary forests to swidden can have significant erosion effects. The claim is that swidden accelerates annual sedimentation by 900% compared to secondary forests on catchment of 30 hectares area (Sarrailh and Raktomanana, 1978).

However, because we do not have data on what proportion of the downstream flow is comprised by the Vohitra, downstream flooding losses are not considered in our study. Also, our data for an analysis of soil erosion losses is insufficient to consider those effects. Therefore, only crop losses from flooding in the vicinty of the park and buffer zone are analysed. As shown in Table 3 these impacts are sizeable, but still may underestimate the total watershed protection benefits of the project. If there is an error, it is on the conservative side.

Moreover, there is a crucial equity issue that needs to be considered. The benefits and costs of watershed protection are not borne by the same set of people. While the benefits of reduced flooding damage accrue to the farmers who practice paddy cultivation in the valley bottoms in the immediate downstream, the costs are borne by the locals who used the forests of the Mantadia National Park area for their sustenance. The local residents depend upon the forest lands in the Mantadia National Park for fuelwood, timber, grasses, palms and aquatic food and for swidden agriculture (Shyamsundar, 1993). These two groups are not necessarily the same. Even if the net benefits are positive, this is true only at the aggregate societal level. Therefore some form of transfer mechanism from the beneficiaries to the cost bearers should be considered on grounds of equity.

This analysis has illustrated the complexities of combining several disciplinary approaches to implement the productivity method for valuing environmental changes. Remote sensing expertise was used to conduct an extensive analysis of maps and satellite images to estimate the deforestation history in the study area. Techniques from soil and hydrologic sciences were applied to data on watershed runoff and river basin flow rates to provide input on the effects of deforestation on flooding in the Mantadia area. Finally, the information about flooding was combined with agronomic information on crop yields to estimate the agricultural economic impacts of additional deforestation, and subsequent flooding, in the absence of the park.

Because of limited data and resources this study is properly viewed as exploratory, but it illustrates the type of data and skills necessary to apply productivity analysis to examine the watershed protection benefits of tropical forests. A large volume of secondary data were compiled and reanalysed by the study participants to shed light on the necessary physical, biological and economic interrelations. This study represents one of the most comprehensive efforts that we are aware of to conduct an integrated economic and ecological analysis. While there have been several conceptual studies in the literature describing the approach used in this study (Gregersen *et al*., 1987), empirical work has been lacking, apparently due to data unavailability. One implication from our work is the need for building country capacity to monitor natural resource changes in developing countries. By constructing geographic information systems and carrying out hydrologic assessments, government and university researchers can build the data bases over time that are necessary to conduct integrated economic-ecological analyses. Our study also demonstrates the need to use spatial and temporal analysis to understand the dynamics of land use, hydrology and economic welfare. In conclusion, we would recommend that future research projects be designed to shed further light on these complex and important interrelations, and on the human-ecosystem interface.

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APPENDIX 1

Estimation of Deforestation Rate (d)

Two factors, *slope* and *elevation*, influence the rate of deforestation in this region. Typically, higher slopes and greater elevation regions have experienced lower rates of deforestation in the study area (Green, 1993). While estimating d, defined as the average annual percentage loss in forest cover, only the 1976–1984 figures are considered because this reflects the most recent trends in land use. It is assumed that both elevation and slope have a equal influence on the deforestation rate, i.e. each has a weight of 0·5.

From the figures and maps used by Green (1993), the protected area (core plus buffer) can be located at an elevation of range 800–1200 m. In the 8 years between 1976 and 1984, this elevation lost 9·1% of its forest cover. Therefore the annual rate of deforestation was 1·14%. This was the elevation component of d.

We ascertained that the protected area lies in three distinct slope categories: 25% in the 0–4 degrees slope range, 50% in the 4–8 degrees range and 25% in the 8–12 degrees range. These three regions lost 25%, 24·7% and 27·7% of their forest cover, respectively, in the 8 years. Therefore, the annual deforestation rates by slope are 3·46%, 3·09% and 3·13% respectively. The weighted average of these three rates is 3·19%.

Finally combining 1·14% and 3·19% in equal proportion, we have a weighted annual deforestation rate of 2·17%. At an annual deforestation rate of 2·17%, all the forests in Mantadia (the protected area) will disappear in 46 years.

APPENDIX 2

Pearson Type III Distribution for Flood Frequency Analysis

Using the 27-year record of Vohitra River discharge, two methods were used to estimate frequencies of different magnitudes: the conventional method of logarithmic normal distribution and the Pearson III distribution method. The log normal procedure has been used for many years by hydrologists and engineers and has been used by the Malagasies and French in Bailly *et al.* (1973) and Sarrailh and Rakotomanana (1978) to estimate flood frequencies in eastern Madagascar. The Pearson III method, developed over the last two decades, is now used almost universally in North America for flood frequency analysis because it appears to estimate probabilities of floods with much greater accuracy than conventional log-normal methods (Haan, 1977; Bedient and Humber, 1992). Richter *et al.* (1992) discuss probabilities of floods of the Vohitra River using a series of annual maximum monthly discharges over the 27-year record. We estimated flood frequencies for the Vohitra River using a Pearson Type III distribution with base 10 logarithmic transformation of annual maximum monthly discharges. For this distribution, the peak discharge at selected recurrence intervals (2, 5, 10, 25, 50, 100 and 200 year) were computed with the equation:

$$\log Q_T = M + K_T S$$

where Q_T is the T-year flood from log-Pearson Type III distribution in cubic meters per second; M is the mean of the logarithmic annual mean monthly discharge; K_T is a scale factor that is a function of the skew coefficient and recurrence interval; and S is the standard deviation of the logarithmic transformed annual maximum discharge.

The relation of annual-maximum monthly-discharge to its probability of "exceedence" (the flood recurrence interval) was estimated using U.S. Geological Survey procedures outlined by the Water Resources Council (1977, 1981) in "Guidelines for Determining Flood Flow Frequency." Skew coefficients were estimated using tables found in Bedient and Huber (1992).

APPENDIX 3

Estimation of the "Stormflow Effect"

1. Results from the Perinet experimental watersheds indicate that flooding (stormflow volume) is three-fold greater for a secondary forest catchment than for a same sized primary forest catchment. Catchments dominated by swidden agriculture produced approximately 1·5 times more stormflow than secondary catchments. Combining this information, we conclude that land conversion from primary forests to swidden is likely to result in as much as 4·5 times more stormflow.

However, not all of Mantadia (the protected area) is in primary forests. From a careful analysis of aerial photographs (Shyamsundar, 1993) it was determined that 10% of the core, and 30% of the buffer was in secondary, and the rest in primary, forests. Given that the buffer is twice the size of the core, we establish that approximately 77% is primary and 23% is secondary forests. Thus if all these forests were hypothetically converted for swidden, we are likely to have a 3·8 times increase in stormflow. This figure is merely the weighted average of 4·5 and 1·5 where the weights are 0·77 and 0·23.

Note, as described in Section 4, the stormflow effect will be different for the floods with different return periods, with the larger (100 and 200-year) floods being less affected by land use. Also, we must be careful of the scale factor when extending the results of small catchment studies to large river basins. Though there is no convenient scale factor to adjust for this, we use a factor of 0·126 when adjusting for the size of the protected area as opposed to the size of the entire watershed. The 0·126 factor is ratio of the area in Mantadia to that of the entire watershed (26 787/212 000) hectares.

2. The use of the Pearson III method on the discharge data for the Vohitra River has enabled the construction of a frequency schedule for floods of different magnitude. As has been stated in Section 4, land use changes affect the smaller and median floods more than the larger floods. In fact it can be argued that the stormflow of the 100 and 200-year flood is unlikely to register major change due to any land use changes, even conversions from primary forests to swidden. For the other extreme, it can be assumed that the 2-year flood will experience 3·8 times increase in its stormflow. The intermediate

floods are likely to register increases in stormflow that are a fraction of 3·8. Thus we have fitted a negative logarithmic function that approximates this relationship such that the stormflow magnification for the 2-year and the 100 and 200-year floods, are 3·8, 1 and 1 respectively. The functional form is:

$$S=[-\log(Q_T/B)+A]$$

where S is the degree of magnification or the "stormflow effect", Q_T is the stormflow associated with each flood event as estimated by the Pearson III method, and A and B are parametric constants equal to 0·87 and 5·29 respectively.

This function produces the following for each flood magnitude:

return period (years)	2	5	10	25	50	100	200
stormflow effect	3·8	2·59	2·07	1·59	1·30	1·0	1·0
annual growth-stormflow	0·03	0·021	0·016	0·01	0·006	0·00	0·00

The number for the 200-year flood has been normalized to 1. As stated in Appendix 3, the entire weight of this storm flow effect will be realized in 46 years. To estimate the annual growth of this effect for each flood magnitude, we need to solve for g in the following equation: $(1+g)^{46}=$stormflow effect (as expressed in the above table). For example, the annual growth rate of this stormflow effect is 3% for the 2-year flood. The table above reports the annual growth rates for floods of all magnitudes.

APPENDIX 4

Estimation of Agricultural Yield Loss

1. We assume that the damage potential of any specific flood type is proportional to the amount of stormflow that is associated with that flood type, except for the centennial flood. Based on expert opinion reports, we assume this 100 year flood is equivalent to the 200 year flood in the destruction of crops. In general, the growth in damage potential (or damage), for each flood type, is assumed to grow at the rate at which the stormflow volume grows.

2. Data were available on the area affected by the 2 and 5-year flood (Ferraro, pers. comm.; Rasolofoharinoro, 1988). Furthermore, the effective flood plain is 654 hectares. This effective flood plain is defined as the maximum area under paddy in the watershed that is in danger of complete damage due to local flooding. Also, this calculation of maximum incorporates the scaling down of the stormflow effect given the size of the protected area relative to that of the entire watershed. It is assumed both the 100 and the 200-year floods, attain a maximum destructive capacity, in that all 654 hectares will be inundated and completely damaged. Using this information and the assumption in note 1, we have constructed a logarithmic function that captured the damage potential of this schedule of floods. The functional form is:

$$L=C^{-1}\log(T)$$

where L is the percent of agricultural crops lost in the floodplain, T is the return period for each flood event, and C is a constant term.

return period (years)	2	5	10	25	50	100	200
% of agricultural crops lost in the floodplain	13·1	30·4	43·5	60·8	73·8	100	100

Note that in the absence of agronomic field trial data on actual yield losses, this functional form approximates the relationship between floods of increasing magnitude and the crop losses. The damage potential increases over a range of increasing flood magnitudes, but the growth is at decreasing rate.

3. Although the probability of a 2-year flood is 0·5 we need to use a conditional probability of damage when we have a range of floods. This stems from the assumption that in a particular season, the simultaneous damage caused by floods of two different magnitudes is not possible. In fact, it will be the effects of larger floods that will be considered because any large flood will damage everything that a small flood would have damaged, but not vice versa. Thus, the *conditional* probability that we use, is the likelihood of a flood of that magnitude *having the potential to damage crops*. By this argument, the 2-year flood can be damaging only if the 5, 10, 25, 50, 100, and 200 are not happening simultaneously. Similarly, the conditional damage probability of all other flood magnitudes is calculated.

4. The dollar-value of the damage caused by floods of each magnitude is the product of the conditional probability, the area inundated, the growth in damage potential and the net return per hectare. This value increases with time because of increase in the damage potential with time. Note that there is no increase in damage for the 100 and 200-year floods.

APPENDIX 5

Estimation of Net Returns per hectare

Labour Inputs (per season, per hectare)	150 labour days
Wage rate (per labour day)	1035 fmg
Cost of Labour Inputs	155 250 fmg
Capital Inputs (per season, per hectare)	
seed	4055 fmg
shovel	1165 fmg
antsy	1239 fmg
spades	5353 fmg
insecticides	2118 fmg
fertilizers	2830 fmg
Cost of Capital Inputs	16 760 fmg
Total cost of Inputs	*172 010 fmg*

Yield (per hectare)	1350 kilograms
Market Price of 1 kilogram of paddy	500 fmg
Gross Return (per hectare)	*675 000 fmg*
Net Return (per hectare)	*502 990 fmg*
Exchange Rate (number of fmg per $)	1110
$ value of net return	*453·1*

Source: Shyamsundar (1993) and Ferraro (pers. comm.).