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# Inland Erosion Hazard Assessment and Mapping for Antigua, Barbuda and St. Kitts

## Post-Georges Disaster Mitigation Project in Antigua & Barbuda and St. Kitts & Nevis

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# 'Inland' Erosion Hazards in Antigua, Barbuda and St. Kitts

This discussion covers the most common modes of erosion in the target states. The states cover a variety of climatic zones from semi-arid to perhumid, which encompasses almost the whole range of possibilities, although the drier landscapes are more common.

## Erosion hazards

'Erosion' covers several types of process; the word is an inclusive term for the detachment and removal of soil and rock by running water, wind and mass movement. Although mass movement is usually thought of separately from "normal" soil erosion, it is, in some parts of the Lesser Antilles of equal or greater importance than " normal" erosion in forming the landscape and in causing land use problems. This discussion will deal with erosion by flowing water, mass movement and wind. Erosion by solution will be omitted. Although it is of great importance among youthful volcanics in the wetter islands especially, and of some importance in relation to the limestones in both Antigua and Barbuda, it is not capable of effective analysis, given available data. In some areas of Barbuda in particular, it could prove to be a hazard, as a trigger of rock fall.

The hazards caused by erosion are not confined to removal of soil and rock. The discussion includes consequent deposition, which can be of greater impact or at least more obvious in its impact on land use and human activity than the removal of material.

## Outline of the procedure for modelling erosion hazards

Erosion is a landscape-forming process which has been the subject of observation in relation to agriculture, because of the tendency of most agriculture to accelerate natural erosion processes. Observations have been of two kinds:

- surveys, usually rather simple subjective, semi-quantitative estimates of, for example, the effects of rain or wind storms on soils;
- controlled studies of sample plots, in which the effects of several environmental variables which appeared likely to influence erosion levels were isolated.

These observations have led to the development of empirical models of which the best known is the "Universal Soil Loss Equation" (USLE), which is widely useful in conceptualising the process, but much less useful as an estimator of erosion losses or of potential erosion outside its home territory. Two primary concepts are that each identified soil type has an intrinsic *erodibility* which depends on its chemical and physical makeup and that each rainstorm has an *erosivity* which can be assessed, based on the kinetic energy of the falling raindrops. The latter is, however, something for which a universal estimator is not available and a term which has had very different interpretations in differing environments. A third at least equally important concept is that of the modifying effect of vegetation on erosion processes.

As a land-forming process, erosion is also a very important part of geomorphology, where its role in the development of slopes and stream courses, and thus of natural landscapes, means that more attention is paid to the differing impacts of "normal" and "extreme" events than in the agricultural view. The geomorphological viewpoint contributes a broader areal view of erosion hazard and engineering studies have contributed to a more quantitative approach.

The models used in this study have been developed using both the agriculturists' and the geomorphologists' understanding of the apparent processes involved and the role of various land characteristics in these processes, to produce mechanistic empirical models which estimate the effects of the apparent processes.

Models similar to these are widely used in the absence of local experiment and the kind of local data which engineers might provide.

The data used in these models is often a simpler version of what appears to be the appropriate data, which are used because they are available and the "better" data are not.

## Review of the data available for modelling erosion hazards

On the whole the data available for this study at relatively short notice was disappointing. In particular it was not possible to obtain aerial photographs. They were simply not available, although some, apparently incomplete, recent sets are present in the respective islands. Data obtained, by discipline, include:

1) *Topographic data* are required for determination of slope angles, orientations and shapes, relative positions, watersheds, stream courses.

*Topographic mapping* for Antigua was only available with difficulty: only an old 1: 50 000 Tourist edition which was poor for the purpose could be found. A print from a badly water-damaged transparency of the 1:25 000 topographic series was obtained but was unusable in practice. Maps at 1:5 000 could have been obtained but would have required far too much work in organising data in the time available. This, combined with the unavailability of air photographs, was very disappointing. Better topographic information can be made available at low cost and could quickly provide slightly better resolution of differing degrees of erosion hazard.

2) *Physical geology-tectonics / lithology* is required for determining the presence of bedding, fracture planes, strength and erodibility of native rock.

Reasonable maps were available for all 3 islands, from the work of Martin-Kaye in the 1950s. Later material was confined to assessments of economic potential. The base on which the geological maps were drawn is not adequately known. That for St. Kitts is named (J A Burden 1920) but has not been traceable. Since the order of precision is not high, and not expected to be, this should not be a problem. Providing better information for the whole area would require a considerable amount of fieldwork and analysis of remotely sensed images, but a quick evaluation of roadsides would be helpful in pinpointing locations where road construction predisposes slides or rock falls.

3) *Geomorphology* can be interpreted from the topography and geology but existing interpretations would be useful for determining land and stream course stability.

The soil reports contain outlines, but more detailed interpretation from imagery is needed for detailed landslide probability. Generalisations have been made from field observations and topographic maps. Perhaps this can be remedied or improved later as the time and fieldwork required would be limited.

4) *Soils* information is required to indicate the erodibility of the material, its depth, freedom of drainage, cohesiveness and other characteristics related to both rain erosion and mass movement. Soil reports are sufficiently detailed in terms of both mapping and soil description for Antigua/Barbuda, but some minor supplementary information was required in St. Kitts. Erodibility measurements were unavailable, but expected differences in behaviour between the major soil types are wide enough for this to be unimportant. Improved estimates would require field experimental work and are unlikely to be worthwhile

5) *Climate– weather*. Rainfall, especially the detail of rainstorms (kinetic energy of the fall / hourly data), is important for the Erosivity term in rainwater erosion. Frequency of dry conditions and very wet conditions are important for wind erosion and mass movement. Wind is needed in similar detail and both rainfall and wind are needed for each site, which is a difficult proposition, especially for wind.

St. Kitts has the best rainfall data collection (for monthly means etc., for numerous stations), but no measurements for periods shorter than a day were available (6 hourly data from recording gauges are

aggregated to a 24 hour period for the record). Erosivity can be estimated from other data but the whole question of achieving a meaningful use of it without local research is moot. In the end, although daily rainfall figures were obtained, they offer no advantage over the use of an interpretation of annual rainfall in making local comparisons. However it would be possible to use automatic weather stations to produce, over a period of a few years, sufficient intensity-duration frequency data to provide much better answers for erosivity and several questions in the hydrology which are presently based on poor data.

Wind erosion is significant in Barbuda and parts of both Antigua and St. Kitts, on susceptible soils with a lack of vegetational cover, but wind data is available only in rudimentary form and only for airports. Examination of weather records is required to give a quantitative estimate of the frequency of suitable conditions (that is soil surface dry, accompanied by winds of force 5 or greater), using a complete daily weather record over a period of 10 years. This kind of data would take around 3-4 weeks to analyse if synoptic data can be made available.

6) Present and antecedent Land Use / Vegetation. The most important single factor in determining the likelihood of erosion is the nature of the land cover, and antecedent land use is an important modifier of both soil erodibility and some aspects of mass movement.

In both Antigua and St. Kitts, a map of Land Use with projections for future land use was available, although in the case of Antigua its categories are rather broad for erosion hazard interpretation. The Antigua map could not in the end be used because of the difficulty of converting the data to a format that could be used. In light of the extensive amount of land devoted to sugar cane, the St. Kitts map has been successfully used with minor modifications. In Antigua, a suitably detailed map of land use has not been produced in years (ever?) but would take only a few weeks to complete using air photo or satellite interpretation. This would provide the most cost-effective means of improving the pinpointing of erosion hazards.

7) *Current status of erosion / landslide*, can be helpful in justifying a model, but it is necessary to be sure that any divergences from the average distributions used in the model are taken into account.

Comparison with previous work (soil reports and another project in St. Kitts) was effective in conjunction with field study with local counterparts. The evidence for soil erosion by water (other than landslides) has mostly been covered up by subsequent regrowth and comparisons with the situation in the 1960s show little basic change. In St. Kitts and in Antigua, the popular perception of erosion damage concentrates on the erosion of valley or ghaut sides, where infrastructure is threatened or damaged.

8) *Hydrology* In view of the concern about valley side erosion a simple model has been developed to estimate relative susceptibility. This required delineation of stream basins, which was difficult in the case of Antigua, given the scale of the topographic maps available. Although watershed mapping is believed to have been carried out in the late 70s or 80s no contact was able to point to the work. The topographic information referred to above could be used to remedy this quickly and provide a stream bank erosion hazard estimate.

## Erosion modes, development and applicability of models

### 1 Erosion by raindrops and flowing water

Climate, geology, soil character and vegetation / land cover are the important influences on erosion, but the relationships between the factors which influence erosion are very complex. Vegetation, for example, is dependent on climate and on soil. Vegetation in turn influences soil development and properties and protects soil from erosion. By comparison with the high run-off from an eroded catchment, a well-vegetated catchment with a permeable soil will experience higher infiltration, lower surface runoff and less

surface erosion. Indeed, in the Lesser Antilles in some places, 'normal' erosion does not occur under natural vegetation and land form development is by solution and mass movement.

Erosion is usually described as a function of:

- the eroding power or **erosivity** of raindrops, running water, and sliding or flowing earth masses, and
- the **erodibility** of the soil.

Erosivity is the potential ability of a process to cause erosion. For specified soil and vegetative conditions, one storm can be compared with another and a quantitative scale of values of erosivity created.

Erodibility is the vulnerability of a soil to erosion. For given rainfall conditions, one soil can be compared quantitatively with another and a scale of erodibility created. Erodibility is usually thought of in two parts:

- the characteristics of the soil
- the effect of treatment of the soil beneath land use

These factors operate together and have been expressed in the "Universal Soil Loss Equation" (USLE), which is described in an appendix. It was derived from studies on standard plots in the USA Cornbelt and it has not been applied to areas with a complete natural vegetation cover. It does not apply to soils being eroded by mass wasting processes, that is the sliding or flowing earth masses, which require a different kind of model, described later. Nor does it cover wind erosion, or losses by solution. However, it demonstrates the inter-related factors which influence the rate of "normal" soil erosion. Modified versions have been developed and applied in other parts of the world. These methods are for use on fields or slopes of limited area and they cannot be used for studies of drainage basins, where effects from nearby or adjacent areas need to be considered. On the other hand, for specific locations where an estimate is required and more data can be obtained (slope length, detail of land use) than in the general assessment, it can be used to modify a classification from the general assessment (up or down)

An alternative way of expressing the factors affecting soil erosion, etc., can be summarized in a descriptive equation:

$$E = f(C, T, R, V, S, \ldots [H], \ldots)$$

*where C*= climate, T = topography, R = rock type, V = vegetation, S = soil character, to which further factors such as human interference (H) may be added. Attempts have been made to express the variables in quantitative terms but because of the extreme complexity they are few and probably never transferable. The human factor dominates through modifying other factors, as when land use is changed, topography is modified by land forming,/ landscaping, conservation, and infrastructure development and soils are changed by the chosen husbandry. Human disturbance has disrupted the balance between soil formation and soil erosion in many parts of the Lesser Antilles, where soil development has taken place under natural vegetation at a rate greater than the rate of erosion. In some areas it is plain that because of an impenetrable layer below the soil, there can have been no significant net erosion over many thousands of years or the soil would by now have disappeared. During man's period of occupation some such soils *have* disappeared (for example, the so-called "Shoal" soils of the leeward side of several islands, have been very largely removed.)

**The climate factor and raindrop erosion**

The climatic factors that influence runoff and erosion in the tropics are precipitation, temperature and wind. Precipitation is obviously by far the most important. Temperature has an effect on runoff by contributing to changes to soil moisture between rains. The wind effect, which is fairly common in St. Kitts, Antigua and Barbuda, includes power to pick up and carry fine soil particles. It also affects the impact of raindrops on the soil.

Raindrop erosion is responsible for:

- disaggregation of soil aggregates as a result of impact
- minor soil creep
- splashing of soil particles into the air
- sorting of soil particles, perhaps forcing fine grained particles into soil voids reducing infiltration rate
- selective splashing of detached particles

Wash is the process in which soil particles are transported by shallow sheet flows (overland flow).

Raindrop erosion is controlled by the resistance of the soil and the amount, intensity and duration of the rainfall. The nature of individual storms varies quite a lot. The size of raindrop may vary although larger drops near 5 millimetres size usually break into smaller drops. During a storm the rain is made up of drops of all sizes but low intensity rain is usually made up of small drops and high intensity rainfall has a greater proportion of medium and large drops. The velocity of fall of raindrops depends on the frictional resistance of the air; larger raindrops achieve higher terminal velocities than small ones. The kinetic energy of the rain can be determined from the size of raindrop and knowledge of its terminal velocity. The nature of storms varies throughout the world and the data required to estimate the kinetic energy of storms, although available at the time of the storm, is seldom recorded and made available for analysis, so that few parts of the world have useable data. Attempts made in parts of the tropical world, especially Africa, have arrived at estimates for kinetic energy and erosivity between which there is a good deal of variation, to say nothing of difference from the USLE standards. Correlations between erosivity of rainfall and total annual rainfall have been attempted and they may work as a good approximation for a particular region or locality but sufficient data to relate the kinetic energy of rainfall to whole year rainfall is seldom available. In our case we have to accept a simple approximation which is that overall erosivity is directly related to total annual rainfall. This is justifiable on the basis that, within the areas considered, the nature of the rainfall received differs much less than the frequency of the rainfall events. Values between 30 and 150 were therefore used.

Raindrop impact on bare soil compacts the soil surface and disperses water from the impact in lateral splashes sometimes containing soil particles. Soil surface compaction by impact is in the case of many soils, enhanced by selective movement of fine grains of soil into soil pores to create a sealed crust, which can be as much as 3 millimetres thick. Although this varies dependent on soil physical characteristics as well as the kinetic energy of the storm, soils with high clay content, effective coatings of free oxides, and high organic matter contents are usually much less prone to crusting than lighter textured soils. (In our soils, some of which contain much free oxide, the several clay species, none of which is predominantly oxide coated, differ in their resistance.) Aggregates at the soil surface are broken down but those below the crust are protected. The major effect of the crust is to reduce infiltration capacity.

**Topography - steepness and length of slopes**

Most experimental work on the slope effect has assumed that the slopes are under cultivation, and obviously dense vegetation will reduce the effect of slope except under prolonged, very intense rainfalls. Raindrop splash will move material further down steep slopes than gentle ones, thus there is likely to be more runoff and its velocity will be faster. The amount of erosion therefore is not just proportional to steepness of slope, but rises rapidly with increasing angle. The relationship is given by:

$$E \sim S^a$$

where E is erosion, S the slope in percent, and a is an exponent. The exponent we are using is 1.55, based on a guesstimate from other experience.

The length of a slope has a similar effect on soil loss because on a long slope there can be greater depth and velocity of overland flow and rills develop more readily than down short slopes. The relationship can be expressed as:

$$E \sim L^b,$$

where E is soil loss per unit area, L is length of slope and b is an exponent. We would use an exponent of 0.6, again a guesstimate, but attempting to generalise values of slope length for whole catchments proved impracticable for St. Kitts and Antigua and was abandoned. At a specific site, a field observation would be worthwhile.

**Vegetation**

Vegetation effects include:

- interception of rainfall by the canopy
- decreasing of velocity of runoff
- root effects in increasing soil strength, granulation and porosity
- transpiration leading to drying out
- insulation of the soil against high temperatures

Interception of raindrops by vegetation prevents drops from reaching the soil and allows water to be evaporated directly. It also absorbs the impact of raindrops and prevents detachment. Slowing down of runoff through vegetation increases the time for infiltration. The presence of roots and organic materials, which maintain soil pores, also maintains maximum infiltration and thereby reduces overland flow and the entrainment of soil particles. Litter accumulation forms a complete protective blanket in most forests and sometimes in grassland, but lemon grass, a common invader of dry (and even rain-)forest in the Lesser Antilles, and a particular problem in Antigua offers much reduced protection, because of its tussock habit

The effects of different land use / land cover are applied to the bare soil estimate of erosion hazard as a factor with values between 0.0001 and 0.6. Details are in an appendix.

**Soil erodibility**

Erodibility is even more difficult to measure than the erosivity of rainfall and no universal method has been developed because erodibility depends upon so many factors. There are two groups: actual physical features of the soil and management of the soil. Many attempts have been made to relate the amount of erosion from a soil to its physical characteristics. Stability of aggregates is the main inhibitor of erosion by raindrops and has been the subject of most studies. A bare soil is a rarity under natural conditions and the means by which the soil has been rendered bare must have an effect (how large?) on its characteristics. In the high rainfall areas of the islands at least, and probably almost everywhere through the islands, soil erosion under undisturbed, more or less mature natural vegetation, is effectively zero. The effect of clearing by man and burning off of vegetation under volcanic events has produced most wash, rill and gullying. Only some kinds of mass movement—landslides, etc.—clearly occurred naturally under natural mature vegetation. The relationship between the natural soil and the bare cultivated soil is not simple and soil characteristics measured from one state are unlikely to provide good guidance for another state. Only specific local investigations will reveal the relationship clearly.

Most experimental work has been carried out using sample plots in the field where natural rainfall can be measured and soil washed from the plots collected in troughs at the downslope end of each plot. Sediment yield can be related to rainfall and the various forms of land management and vegetation cover used in the different plots. The inventors of the USLE were able to produce a nomogram that calculated an erodibility estimate from a few simple soil related factors. But in practice this is not widely applicable; it could not be without the recognition of other factors which are of zero importance in the Cornbelt, just as some

Cornbelt factors may be of zero importance here. The important fact is that, whatever the level of erodibility of bare soil, its limits of variability are less than the variability produced by management: erosion is largely controlled by the type of land use management the soil receives.

The estimation of K (erodibility) used here follows concepts modified from those used in the USLE and added considerations, which in effect incorporate the important underlying-geology factor.

K estimation

$$K = Dr + Dp + St + T + C + Pt + Ps + Om$$

Where:

Dr = drainage on a scale -1 to 5
Dp = depth of soil on a scale 0 to 5
St = surface stone -2, 0
T = soil texture on a scale 12 to 47
C = clay type/ion saturation -6 to 3
Pt = ped type/size on a scale -4 to 0
Ps = ped strength on a scale -2 to 2
Om = organic matter % -6 to 0

The details are given in an appendix.

## Wash, rill, and gully processes

Running water removes soil from slopes by a variety of processes: sheet wash, rilling, gullying, and also piping, which is probably rare and irrelevant in our situation.

### Wash erosion -detachment and transport

Soil particle detachment, the destruction of peds [natural soil aggregates] by *raindrop impact* can occur anywhere soil is exposed to the force of raindrops. Detachment by *runoff* is limited to the small portion of the land area where runoff concentrates and flows at erosive velocities. The size and quantity of particles transported by runoff is a function of runoff velocity and turbulence, which increase as slope steepens and depth of flow increases. Overland flow rates commonly range up to one foot per second, enough to move silts and fine sand. Once entrained, a particle will remain in suspension until a lower, depositional velocity occurs.

Conditions of flow vary greatly over short distances. As we can see on any bare slope after tillage followed by rain, the micro-relief of the surface correlates with patterns of "scours", sediment fans and debris micro-dams. These irregularities make it unlikely that the movement of water and particles across the surface can be modelled by present means, or that it may serve any useful purpose in our kind of application.

### Rilling

Rills are usually defined as "micro-channels... small enough to be removed by normal tillage operations" (FAO1965). A more general definition is "small channels with cross sectional dimensions of a few centimetres to a few decimetres." Rills are usually discontinuous, may have no connection to a stream channel, and often disappear between one storm and the next or during a storm. Rill erosion is usually considered to be the primary agent for sediment transport on slopes with little vegetation and estimated to carry between 50 - 90% of the sediment removed. We have insufficient actual quantitative observations, but sheet wash appears to be more important than rilling within our area.

The loss of soil by raindrop, wash and rill erosion appears to be related to two types of rainfall events:

- short-lived storms of high rainfall intensity in which the infiltration capacity of soil is exceeded, and
- prolonged rainfall events of low intensity which saturate the soil

The former are probably more commonly significant, although the rainfall is lower in the lower infiltration capacity soils of Antigua than of St. Kitts.

***Model developed for sheetwash and rilling hazard***

The following information was considered:

- *underlying geology*
  1. Permeability– likelihood of soil saturation / rapid drainage not used
- *soil*
  1. "Erodibility" (K)

  (2.) Surface condition (structure etc, incorporated into K)
- *geomorphological situation / hydrology*
  1. Length of slopes, (However this could not be mapped from the existing information)
- *slope angle* (S)
- *rainfall*
  1. "Erosivity": the mean annual rainfall is the only relatively accessible mapped data. Its relation with kinetic energy was estimated, but is poor
- *landuse / land cover*
  1. Factor for protection by vegetation / land cover

The final model used for rill and sheetwash erosion hazard is:

$$\text{Sheetwash and Rilling Hazard} = K.\ R.\ S^{1.55}.\ LU$$

where K = soil erodibility, R is the rainfall factor, S is the tangent of the slope angle in degrees and LU is the land use factor.

**Consequences of rill and sheetwash erosion and deposition**

Rill and sheetwash erosion is mainly of consequence for farming operations. Surface erosion, until far advanced, mainly affects the part of the soil most valuable for farming, the organic topsoil. Losses of topsoil mean losses of nutrients, nutrient and water holding materials and the part of the soil with structure best suited to permit water to enter the soil. Losses of one or two centimetres—the maximum likely loss over a few years under normal conditions here—will probably not bother anyone else, but are critical for farmers.

Deposition of a "float" of fine materials at the foot of a slope on a farm may destroy crops and make tillage more problematic. By contrast a float of materials on a road may mean a few hours of inconvenience and some work for a machine—hardly a major problem.

**Gully erosion**

A gully is arbitrarily defined as a recently extended drainage channel that transmits ephemeral flow, has steep sides, a steeply sloping or vertical head scarp, a width greater than one foot, and a depth greater than about two feet. Gullies may form at a break of slope or break in the vegetation cover when the underlying

material is mechanically weak or unconsolidated or by deepening of a master rill. Gullies are therefore most common in such materials as volcanic ejectamenta, alluvium, colluvium, gravels, partly consolidated sands, and debris from mass movements. Gullies also develop in weak argillic rocks—argillites, phyllites, mud rocks, and shales. These gullies are often channels through which debris flows and mud flows with very high sediment discharges, drain unstable catchments, perhaps typical of some stages of volcanic landscape development here.

Gullies are usually not regarded as features of "normal" erosion but the result of changes in the environment, such as burning of vegetation, overgrazing, climatic change affecting vegetation, extreme storms or any other cause of a break in vegetation which will bare the soil. The ghauts of St. Kitts appear to be large gullies which probably formed either during the initial bare rock conditions after pyroclastic flows, or associated fires, and at least in part as a consequence of early sugar cane cultivation. Gully erosion nearly always starts because there is either an increase in the amount of flood runoff or the capacity of water courses to carry the flood waters is reduced. That is, if streams and their lesser feeders cannot carry the load, gullies are likely to be initiated.

The capacity of a stream channel depends on cross sectional area, slope and roughness. An increase in the resistance to flow by the growth of vegetation in, or at the edge of, a channel will cause an increase in roughness and be accompanied by a decrease in velocity of flow. This reduces the capacity of the channel to accommodate flood flows and increases the chances of flood waters overflowing the banks. By contrast, a reduction in vegetation along the waterway may cause a decrease in resistance to flow, a decrease in roughness and increase in velocity, with possible development of channel scouring. Any local effect can upset the existing equilibrium. Starting points could be cattle tracks or the diversion of drainage by a new road so that instead of spreading over a whole valley floor, flood waters are diverted into confined areas with less resistance to flow.

***Model developed for gullying hazard***

The model for gullying simply used an assessment of the depth and nature of the soil and the nature of the underlying rock to determine whether the conditions for gullying (more than 3 feet of erodible material is the suggested criterion) existed, using interpretation of the soil and geological information available and combining this with the rill model. The rill model effectively states the potential level of erosion (the 5 classes). Excluding areas not susceptible to gullying provides classes for gullying

The following information was considered

- all the elements of sheetwash and rilling, and
- *soil*
  3. deep soil
- *underlying geology*
  2. presence of deep soft underlying materials
- *geomorphological situation*
  2. long straight slopes or large amphitheatres present in river basin (However this could not be mapped from the existing information – and long straight slopes can only be meaningful as applied to specific sites)

Gullying Hazard = (Rill Hazard). (gullying susceptibility of soil - rock combination: 0, 1)

**Consequences of gully erosion and deposition**

Whereas the consequences of sheetwash and rill erosion are usually serious for farmers and less serious for others, rapidly developing gullies could be more serious for other land users than for farmers, through the need for costly controls to avoid further expansion and the disruption of works already underway. Farmers may be able to contain gullies by using simple bush dam structures, filling and covering with vines etc., but for construction sites some kind of diversion may be required.

Deposition at the outfalls of gullies may be deeper than those from rills and gullies and more difficult to deal with. As with rill and sheetwash deposits, they are likely to be found at the foot of a slope where the angle suddenly becomes more gentle.

**Erosion of stream banks**

Erosion of stream banks is rather a special case of rainfall based erosion, because without the canalisation of the drainage system, it will always occur, with or without human influence. Erosion by streams is part of landscape development in this environment, irrespective of vegetation, proceeding all the time, perhaps fitfully with major storms producing the major effects, but also proceeding to a lesser extent every day that the watercourse flows. It is acknowledged nowadays that the major part of stream work, at least in many localities, is done when bank full conditions are achieved. This is something that, dependent on the locality, may happen two or three times a year or less than once a year. Landscapes develop through down cutting by streams in the sections where water is flowing freely under gravity and deposition of eroded material in lower sections or in the sea.

Stream courses fit their environment. Except where there is a marked change in the condition of the drainage basin, where, for example, long-period change in climate or river capture may cause a substantial reduction in flows and then an "underfit" stream may occupy the course cut by a more active predecessor. But this kind of circumstance apart, a stream course reflects the work done by water passing downstream in ordinary, say once a year, storms. If we observe streams carefully we see the small adjustments made from time to time.

When truly exceptional storms occur, however, perhaps once every 200 or500 years, we can expect to see much different kinds of change—especially the undermining or removal of curves in the stream course, removal of some deposits, and in the meandering lowest parts of some streams crossing flatter areas, the cutting of "cutoffs" and new courses.

Recent experience has affected the general view of this phenomenon. The lower reaches of some of the larger streams have produced some fairly dramatic changes in the case of Antigua during a storm of unusual dimensions (hurricane Lenny), and notable erosion in a less severe storm in St. Kitts. We can expect the largest courses to show the most obvious effects, but smaller sub-catchments will show proportional effects that will likely not be noticed. It is probably worthwhile to predict where these larger effects are most likely, because of their possible effects on infrastructure.

What can be done about it? To an extent we can predict which are the most likely streams to experience severe bank erosion and more importantly we can respect the energy released from time to time by the natural environment. If we allow buildings or roads to be constructed so as to obstruct natural watercourses we had better ensure that we have provided alternative courses of adequate dimensions. Much more practically we should avoid construction on flood plains and ensure that roads crossing them are provided with adequate culverts.

There are other factors besides duration and intensity of rainfall, which influence the kind of flows that cause major changes. Some of these are factors of the natural environment and should therefore already be reflected in the conformation of the stream course– the shape and size of the valley will relate to earlier

storms. But our activities also influence erosion beyond that which would occur under conditions with no major human input.

The various factors include:

**Human activity**

- use which minimises infiltration and accelerates runoff is probably the most important single factor in deciding which streams are going to reach a peak discharge above their capacity under more natural conditions when previous major storms occurred. The sediment load reaching the stream will also be less than in other otherwise similar basins with more exposed soil, where speed and energy will be reduced The hazard will not therefore relate to the erosion hazard of the rest of the catchment. Human habitation areas and agricultural land use need separate evaluation.

**River basin morphology**

- a basin with areas of naturally low infiltration rate and especially with low capacity to hold water (soil type and underlying geology dependent) will also be more likely to reach quick peaks of flow, that is the storm required for basin saturation and rapid flow will be relatively small. In the case of extreme events (200yr, 500yr) this will be important.
- a stream course with many bends, especially tight bends in soft materials, is more likely to alter course and erode than a straight course, and that is the way it is naturally constrained to develop.
- Conformation of the basin and the rainfall distribution through the basin will be important. A steep course may have greater potential for bank erosion, but this may also mean that a straighter course has been established with reduction in vulnerability to bank erosion. When every part of the basin is saturated, the steepness of slope of the stream course may be a good predictor of the effect of a storm. The period during which high flow is experienced will be related to the size and shape of the basin. However these are not simple relationships—and they cannot be modeled without more data.

**Antecedent weather conditions**

- the wetness of the land before the storm: where there is normally a marked slowing down of the effect of runoff from the storm because of the nature of the soil and vegetation, antecedent saturation of the land will kill this effect. With very dry conditions the results will be less predictable. Consequently a heavy storm at the end of a wet period or a long, heavy storm will cause more general problems.

***Model developed for stream bank erosion hazard – by river basin***

The following information was considered, for a storm with uniform characteristics over the whole island:

- *land use*
  1. built-up area as percentage of the basin
- *soils*
  1. likely reduction in possible infiltration (estimated in relation related to land use based soil changes)
- *stream characteristics*
  1. sinuosity of the stream course, estimated for only the lowest one-third of the course, by comparing actual length of the stream bed with crow-fly length

Several assumptions are made to produce an index which excludes extreme events, where every basin becomes saturated and basin characteristics will be critical to flows and erosion. Another assumption is that the lower parts of all the stream courses are cut in unconsolidated or weakly consolidated deposits.

Stream bank erosion hazard = c.(a+b)

where:

- **a** quantity of human habitation– built-up area as percentage of the basin
- **b** likely reduction in possible infiltration–related to other land use (agriculture related vegetation and soil changes)–as ( % land involved * % reduction)
- **c** sinuosity of the stream course, approximate from the map ( length of stream course / length of generalised stream course).

and **a+b** = index of "reduction of infiltration"

*Antigua river basins*

Antigua comprises a relatively elderly landscape or rather several adjacent landscapes:

- limestone areas with drainage that cannot be easily defined;
- central lowland with a complex drainage pattern and several artificial modifications– lakes or ponds along stream courses and cut drains
- old dissected volcanics with generally small steep drainage basins

Overall there is a small number of large rather flat drainage basins and many smaller ones. The large flat drainage basins are possible candidates for major changes of course as well as bank erosion. Without a great deal more information than is available, the estimate was limited to non limestone areas and whole catchments. Effects in small sub-catchments within the large basins could not be calculated effectively and the really small catchments also had to be omitted. The assessment for Antigua was finally abandoned for lack of information.

*St. Kitts river basins*

The landscape of the largest part of St. Kitts is relatively young with rocks variably but mainly poorly consolidated. Within this area, the basins of streams reaching the coast can be divided into three main groups, all of which are more or less radial from the main mountain chain:

- those which have a substantial area in the heights of the mountain range and are generally relatively large in area
- those which occupy a niche between larger basins and originate only near the seaward end of the main glaces slope which surrounds the main mountain chain, and are relatively small, but in some cases very steep
- the majority, mainly of medium size, traversing nearly the full length of the glaces slope

The southeastern peninsula, is comprised of much older relict stumps of volcanoes connected by a mixture of terrestrial and marine alluvium interspersed with salt ponds. The landscape can be divided into fairly obvious basins but there are no obvious permanent streams, and only a few seasonal stream courses.

**Consequences of stream bank erosion and deposition**

The consequences of deposition from stream bank erosion are unlikely to be a great problem, since they will either occur within the stream course, on natural levees or as shallow deposits on terraces. They will in any case be indistinguishable from the general load carried by the stream. Erosion of stream banks simply means adjustment to the course of the river. Unless structures are built within the banks of the river or very close to them they should be insignificant. Where, in the lower parts of a river course, on the flood plain, a meandering river may cut a new course, the area at hazard is somewhat more extensive. However it should

be clear that such areas are subject to flood damage apart from new stream courses and infrastructure construction of any sort there needs justification.

## 2 Wind erosion

A wind erosion prediction equation was developed using wind tunnels and field studies in the US and Canada, commencing in the 1950s, following pioneering observations in UK and North Africa in the 1930s.

### The wind erosion prediction equation

The equation, expressed in descriptive function form is

$$E = f(I, K, C, L, V),$$

where: E is the potential average annual soil loss,
I is the soil erodibility index,
K is the soil ridge roughness factor,
C is the climate factor—perhaps climate and hydrology would be more appropriate in WI circumstances
L is unsheltered distance across a field, and
V is the equivalent vegetative cover.

This is the most widely used method for assessing average annual soil loss by wind from agricultural fields in the US and probably some other countries. It is plainly beyond the scope of any assessment that can be made quickly in the East Caribbean with the prevailing lack of data, both instantaneous wind speeds and wind-erodibility of the soil, to say nothing of field micro-relief which is highly variable and dependent on management practices. This is a useful starting point, but quantitative estimates are unnecessary in the present study.

### Wind erosion mechanisms

Wind erosion is the consequence of three related transport processes, movement of soil particles under the force of the wind:

- in suspension—mainly grains <0.1mm diameter » very fine sand and silt
- by saltation—mainly grains 0.1 to 0.5 mm diameter » fine sand
- by surface creep—mainly grains 0.5 to 2.0 mm diameter » coarse sand

The lifting of fine particles into suspension may help to break soil peds, but the effect of particles bouncing along and striking the surface in saltation is probably the major one in reducing otherwise stable soil peds to a moveable size. Surface creep of larger particles /aggregates is aided by the pushing effect of the materials in saltation and must also produce some smaller fragments, by wear and tear. It is clear enough that there is a size range of primary particles and aggregates which is preferred by these wind transport processes, but organic particles which are usually less dense are also preferentially selected

### Onset of wind erosion and observations required for prediction

Soil erosion by wind is initiated when wind speed exceeds the *saltation* threshold velocity for a given land surface condition, which is dependent on the erodible material and surface roughness. The duration and severity of an erosion event depends on the wind speed distribution and changes in the surface condition. To an extent we can estimate the structures and processes that modify a soil's susceptibility to wind erosion but to map them well requires a good deal of field observation, a slow process. However, simple field observations made over the years can give us a very good guide as to the areas at hazard– quite sufficient to make recommendations for prevention or mitigation.

We are, in the case of these islands, in a situation very different from the continental plains in which the research was largely carried out. We do not have vast expanses of land with little cover for long periods and we do not have the dry winds of a continental interior, which reduce both the mass and the adhesion of soil particles. Instead our periods of peak wind force, outside hurricanes, come with the Trade winds, which although not highly humid are rarely really dry.

**Wind erosion in Antigua, Barbuda and St. Kitts**

In the conditions of Antigua, Barbuda and particularly St. Kitts relatively few days are likely to be encountered with weather and surface conditions suited to wind erosion. Soils which are shallow and of low water holding capacity because water-eroded will be more likely to be dried out and therefore susceptible than their uneroded counterparts.

The larger the land area the more likely winds are to be drying, but there is probably no significant difference between the islands with respect to this variable, nor can one be quoted for wind speed, for which the available data is too limited spatially and in terms of details of velocity and duration. Annual rainfall / hydrology and soil characteristics are therefore the only data available which are reasonably useful.

***Model developed for wind erosion hazard where the soil surface is left uncovered***

The following information was considered, for a storm with uniform characteristics over the whole island:

- *soil*
  1. wind erodibility (I)
  2. (surface micro-relief, not available)
- *geomorphological situation / site exposure*
  1. open exposure (this was taken as land cover, where available, but a combination of vegetational cover and topographic position should be used and can be used in field determinations)
- *climate*
  1. (wind speeds, not available)
  2. surface wetness

Two factors only were used, for a situation where the soil surface is left uncovered and where similar wind speeds throughout the island are assumed. It ignores surface variables which we cannot evaluate— no allowance is made for variations in surface roughness related to husbandry. The two factors are annual rainfall, in the form of number of dry months (the higher the number the higher the hazard) and soil characteristics (the larger and more stable the grains [particles or aggregates] the lower the hazard.) Barbuda, unsurprisingly, on areas with parent materials that may themselves have been wind deposited, shows the highest hazard ratings.

**Wind erosion hazard rating = I x DRY MONTHS**

where: **I = T + St + Pt + Ps**

(T = soil texture on a scale 1 - 7.
St = stony surface on a scale -1, 0
Pt = ped type on scale 0 - 5
Ps = ped strength on a scale 0 - 5
**DRY MONTHS** = Number of months with less than 2.4 inches rain, using long term averages

### Consequences of wind erosion and deposition

Wind erosion is usually very damaging to young farm crops, because of the cutting action of particles whipped along by the wind, but tall well developed crops provide their own defence, to a great extent. Clearly enough deposition is governed by wind direction, so that although there will be preferred directions, deposition may take place anywhere. Probably in our conditions only a little material 'flies' in suspension and most 'bouncing' particles will be halted by the nearest bush or building. On the whole, the consequences in the target islands are not likely to be very large. They could be very damaging to some young crops and a great nuisance to other human activity, but not a source of seriously restricted visibility and danger.

## 3 Landslide and Rock fall

### Introduction

*Mass movement*

We are chiefly concerned with landslides and we often call rock falls landslides too, for want of an inclusive term. We need the term "mass movement", although it is not well known.

Mass movement describes a wide spectrum of land surface movements which are not detachment and transport of particles through the media of water or wind, but larger scale movements under gravity, even where water may be a lubricant or the force of rain a trigger. Mass movements of soil and underlying rocks and other materials under gravity are common under natural vegetation as well as where human intervention is involved.

The hazard is subjectively assessed here, rather like land capability, because several processes and many factors need to be quantitatively evaluated to produce an objective answer. Development of an overall assessment based on models will need to await more investigation of local factors and more data.

The "recipient areas", the sites which are affected by receiving a slide are briefly discussed, but are not shown on the map.

*Two sorts of hazard*

Two sets of circumstances are considered here.

One covers the "normal" hazard— that of a landslide when a piece of land is in its natural state, covered with natural vegetation, or has been / is being used for low intensity agriculture or forestry without excavations and without such major changes to the soil surface as marked compaction or cover by an impermeable material.

The other covers the hazard associated with excavations — and the kind specifically considered are road cuts and excavation of deep foundations for large buildings. In all the mountainous Caribbees and in tropical mountainous countries generally, road cuts traversing steep slopes cause slips unless they are carefully aligned and maintained.

### Kinds of "slide"

The following types of "slide" have been recognised, not in any special order:

1. Flow landslides in allophane and unconsolidated mainly pumiceous ash
2. Planar landslides in kanditic materials, to a lesser extent in smectites and various little-weathered or unweathered materials

3 Rotational landslides in kanditic and mixed materials, the latter mainly in colluvial slopes and usually containing coarse material
4 Rock falls

**Landscapes and hazard of landslides**

Landslides are movements under gravity. Earth materials do not all roll or fall into the sea because other forces hold the materials in place. Rocks and soils may be very cohesive or not at all cohesive, or something in-between. They may be supported in place by underlying materials which are competent, strong and resistant to erosion and fracture or by rocks which are incompetent, weak, erodible or fractured. Or they may be located above a sloping plane which is impervious—an aquiclude—down which water moves and acts as a lubricant, so that a slip is facilitated.

The following factors are involved and should be considered to arrive at an estimate of the stability of any particular location:

*Geology*

- lithology and weathering state of surface and underlying material(s)
- bedding, dip relative to slope of land
- tectonics— is there a high incidence of tremors, are there moving faults / old faults?

*Soils*

- physical characteristics: thickness and porosity, consistence, layering,

*Relief*

- slope angle
- shape of slope and surrounding slopes, plane, convex, concave

*Rainfall*

- quantity and distribution

*Vegetation*

- Cover, kind and rooting

This list cannot be fully met without extensive field observation which would be very time consuming. On the other hand the most important slides from the point of view of disruption to our activities are those associated with roads and to some extent other aspects of infrastructure. Semi-detailed field mapping along almost all present roads, would enable a clearer indication of these hazards to be given.

**Data used**

*Geology*

Consideration of the geology is limited by the quantity of mapping. There is for each island an incomplete (1950s), simple, map which shows areas which have a common suite of materials. Most suites are far from uniform, and in Antigua the distribution is quite complex, such that mapping error due to changes of base, scale and the original level of accuracy of field mapping may mean that some boundaries are difficult to understand in the field. But ignoring the boundary inaccuracies, each unit is different from adjacent units and can be used to distinguish kinds and levels of hazard where more precision about location of individual geological features is not possible. In St. Kitts the mapping is subject to at least the same order of inaccuracy, but because of the more extensive units and the simpler geology, misunderstanding is less likely.

No systematic review of tectonics affecting the islands was available, only general studies. Antigua is the earthquake centre of the Eastern Caribbean. Indications of faulting and episodes of earthquake activity are not documented in a way that could be used.

*Soils*

The soil map gives information about the location of the different soils, classified into groups. There is sufficiently detailed information about the materials, layering, and physical properties to predict stability behaviour of the soils. They are discussed briefly in an appendix.

*Relief*

The slope classes with a different interpretation from that used for surface erosion.

*Rainfall*

The data customarily used for estimating rainfall are "normals" from the period 1930-1960. The 1960 rainfall map used a large number of rainfall stations, widely spread over the island.

*Vegetation and Land Use*

Existing simple maps of these distributions were available from the planning authorities in St. Kitts.

**Observed effects in the Lesser Antilles**

**Vegetation / Land Use**

Recent large landslides in Dominica, and especially series of landslides, have all been associated with removal of the natural vegetation. The same phenomena are common throughout the islands. Wherever natural vegetation is substituted by shallower or less dense rooting plants or simply cleared, mass movement is enhanced.

**Rainfall**

Although seismic activity may provide a trigger (perhaps more than a trigger in Antigua), storm rainfall has been the main cause of landslides in the Lesser Antilles. As the quantity of "development" grows it will be even more important. Some materials have properties when saturated which are very different from those observed in the "normal" dry state. The persistence of rainfall is a very important factor in this. Tuffs and agglomeratic tuffs and especially pumiceous tuffs have very high porosities and the allophane soils derived from them in areas of high rainfall (basically only the Peak areas of St. Kitts) are even more porous. The kandite soils developed from similar materials are much less porous and seem not to exhibit the kind of flow slides common among the allophane soils. However, relatively deep planar and rotational slides occur in kanditic and mixed kandite and smectite materials when the soil mass is saturated and a slip plane of lower permeability is lubricated.

These soil rock combinations lead to larger slides wherever a shallow soil on a steep slope overlies an impervious layer, whatever the vegetational cover. In such areas, a prolonged period of heavy rain will produce landslides. The seasonality of rainfall in the Lesser Antilles means that peak soil water contents will be reached at the end of the wetter season, generally autumn or early winter.

**Relief**

Slope angle

Landslides move downslope. The longer and steeper the slope the more potential energy, but all depends on the balance of gravity, proportional to the sin of the angle of slope and restraining forces— chiefly friction, which is materials-specific. Values are sometimes given for the "angle of repose" above which

various loose materials will slide. The commonly quoted limit is 37°, but that for local volcanic ashes seems to be lower.

Slope shapes

Valley side slopes with benches indicate some difference— a change in material, a change in erosion history; similarly, ridges and re-entrants probably mark a significant change in material. Such changes in material have effect on local landslide hazard.

In apparently uniform materials, straight plane sections, " noses" and amphitheaters all occur as a consequence of the course of the river (which may have had causes other than differences in the valley side material). Downslope flows of water will be spread at the "noses" and concentrated at the amphitheaters. Stream courses develop in part by "headward erosion." It is therefore likely that amphitheaters that are wet enough and susceptible in other ways will be the site of slides.

Mapping such variations requires more detail than we can represent in this exercise.

**Soils**

The soils identified in the soil surveys were defined mainly on texture, clay type and maturity, profile type and depth. These soils can be regrouped in relation to susceptibility to slip.

The clay types have radically different physical properties and the regrouping is based on those differences plus the presence / absence of pans or parent material of different hydraulic properties.

*Allophane soils*

Allophane soils are probably not present in Antigua and Barbuda and are of fairly limited extent in the rain forest / former rain forest area at higher elevations of St. Kitts. These soils (or very young soils developing allophane) are mostly underlain by pumiceous tuffs or similar rocks, which are little different from the soil in such physical attributes as porosity and cohesiveness. These soils are thixotropic and may flow-slide.

*Kandite soils*

Kandite soils are of two main types:

- moderately deep soils, fairly youthful (St. Kitts) over ash and tuffs; older, (Antigua) over tuffs
- deep soils over marl over hard limestone (Antigua)

The shallower soils are relatively stable and are mainly found in locations which appear rather stable, except for stream valley sides, where lateral corrasion may occur and undermine slopes. The deeper soils are candidates for rotational shear slips where they occur in sufficiently steep slopes.

*Smectite* soils

These are very common in Antigua, occupying lower and middle elevations and varied slopes. They can be divided into:

- mainly shallow soils over coarse sediments (gravels, chert etc) in stable locations
- deep soils over tuffs on moderate slopes
- deep soils over clays and sandstones in gentle slopes
- shallow soils over andesite in moderate to steep slopes (also St. Kitts)

In St. Kitts they also include

- moderately deep soils over alluvium in gently sloping locations

All these soils have the distinctive cracking and / or self mulching characteristics. They are inclined to creep under wet-dry cycling, but are very cohesive and only candidates for sliding where they occur as colluvial (creep) accumulations often with admixtures of coarse material.

*Mixed Clay* soils

These are also very common in Antigua. They can be divided into the following groups:

- deep in deep alluvium in valley bottoms
- deep in moderately deep colluvium on gentle valley side slopes
- shallow or very shallow on tuffs and agglomerates

Only the soils over tuffs are in positions where they are likely to slide. In general these soils tend to behave intermediately between kandite and smectite soils. They are candidates for slides.

*Sand or stones, no clay*

These very little weathered soils with no clay development are mostly found on younger volcanics. Some are shallow to solid material, others overlie deep layers of loose blocks. These are very common in St. Kitts and rare in Antigua.

They can be divided into two groups:

- shallow soils on marine and lacustrine alluvium in low lying locations—these can only provide very minor slips
- deep soils on deep multilayered ash of the glacis around the main mountain chain of St. Kitts. They occupy slopes which decline from steep to gentle downwards and are weak and relatively unstable. They are good candidates for slides where the drainage is somewhat impeded.

**Model developed for landslide / rock fall**

The following information was considered:

- *tectonics*
  1. Frequency of activity, nearness to epicentres—only available in general terms, unsuitable for mapping intra-island classes
- *underlying geology:*
  1. Permeability and porosity— will it drain easily, will it hold much water
  2. Cohesiveness of the material—loose, compact, cemented, welded, massive, jointed, cleaved, fractured
  3. Favourable bedding—how well developed, suitable angles, aquiclude planes
- *soil*
  1. Porosity
  2. Cohesiveness
  3. Relation with underlying geology
- *geomorphological situation / hydrology*
  1. Amphitheatre position
  2. Earlier landslides
  3. River cliffs (These require a level of interpretation appropriate to specific sites rather than the general level attainable at the present scale of mapping)

- *slope angle*

  1 Critical angles for stability

- *rainfall*

  1. Frequency of probable saturation

**Landslide hazard = (Soil-rock combination susceptibility). (Slope factor). (Land use factor)**

where:

1 Soil and rock combination susceptibility is defined by the following:

Rock types are classified as:

| | |
|---|---|
| 0 | unsupportive of landslides, either in unfavourable topographic locations, or physically unlikely and unlikely to support rock falls |
| 1 | supportive of soil above sliding, may also support rock falls |
| 2 | likely to slide with soil |

Soil types are classified as:

| | |
|---|---|
| 0 | unlikely to slide, unfavourable topographic position or physical nature, (e.g. red soils of Barbuda highlands among lapiés) |
| 1 | will slide given an underlying slip plane |
| 2 | susceptible of internal slips (e.g. deep kandite soils, rotational shear slips) |

These factors (below, geology first) are multiplied together to produce combined susceptibility score

| | | |
|---|---|---|
| 1\|1 | 1 | shallow debris and possible rock falls |
| 2\|1 | 2 | soil and rock debris slides |
| 1\|2 | 2 | deep debris slides and possible rock falls |
| 2\|2 | 4 | possible major debris slides |

2 Slope factor is defined as:

The effect of gravity is considered using the same slope factors as for water erosion up to angles of 30 degrees and above that is doubled, reflecting the approach to the angle of repose of loose materials, somewhere around 35 to 37 degrees

3 Rainfall factor:

Although rainfall obviously is related to landslides, it is in some islands confounded with soil type and perhaps vegetation and only periods of saturation alternating with drier periods appear to hold a key to slip conditions. In the three islands no critical threshold is evident so the factor was omitted.

4 Land Use factor is given by:

Estimated generalised figures for the effect of vegetation and other land uses relative to bare soil (see appendices). The effect of road cutting is however excluded.

**Hazard score adjustment for road cuttings and construction**

The final scores have been given the same equal area reclassification as other hazards. The distribution of non-zero values is less skewed than for other hazards Where a road or road construction is in view the hazard class should always be raised at least one class.

**Consequences of landslide and rock fall**

Landslides and rock falls can be dangerous. Landslides have engulfed villages and killed people on many occasions in the Lesser Antilles, and there have also been many narrow escapes. Most landslides and rock falls contain relatively small quantities of material which moves only a short distance, but they can still present a threat to life. In steeper lands there is potential for long distance travel but it depends on detail of the topography. It should not be forgotten that a long fall provides the momentum to ride up an opposing slope, given the right topography. Flow slides which are primarily found in allophane soils and little weathered pumiceous ash can travel long distances down quite gentle slopes. In areas where this is possible, it will be worthwhile to check in the areas of highest hazard class whether buildings are in a potential landslide or rock fall path and monitor them. However, the hazard should promote caution and not be allowed to cause an excessive reaction– many buildings in Dominica, a much more landslide prone island, which appear to be prime candidates for landslide damage have existed with the potential threat for many years.

## Comparisons between current levels of erosion and prediction using the models

Objective comparison between current levels of problems and prediction using the models is difficult for relatively rare events. Data for the models were not available before the field visit, so that only the general concepts could be confirmed. While landslide evidence remains clear for some time, and gullying usually also, a realistic assessment of sheet and rill erosion would have required actual digging and was not practical in the available time.

The weather of the last few years has been characterised by events of unusual severity in terms of both rainfall and wind. But this may be an indicator of the increased activity which global warming is likely to make more common.

*Landslides* (rock fall, debris slide, etc) were as predicted: limited in Antigua to superficial soil-only slides on steep slopes in the volcanic area. The paucity of steep slopes elsewhere, and lack of suitable structures are responsible for the low incidence under most rainfall conditions. In St. Kitts there was no evidence of any substantial slides, but undercut sidewalls of ghauts produced minor falls as stream courses adjusted. The road cuts along the main road to the SE produce small rock falls as predicted and will eventually produce one or two major falls or combined slide and fall.

*Soil erosion by water:* sheet erosion is common on the few bare fields in Antigua and some washout of fine materials from the vegetated areas must occur, but the general cover with some exceptions, must be rather protective. In St. Kitts, the level of sheet erosion is very variable with the condition of the cane fields. Obviously most of the cane soils are quite erodible, and evidence was widespread that small bare areas were contributing large quantities to the downslope roads which operate as minor water ways. Smallholdings showed evidence of both sheetwash and some gullying.

*Gullying* requires a concentration of flow and deep erodible materials to be significant. There are few geomorphic situations in Antigua conducive to gullying except in the lowlands where for other reasons this is unlikely. One re-excavated gully on a steep slope was observed, but it had taken an exceedingly heavy downpour (30 inches in 24 hours) to revive it in an area with little room for concentration. In NW St. Kitts the ghauts are simply large gullies. The long straight slopes mean that under suitable land cover, flow can be quite rapid and will concentrate. There was little sign of new gullying (some large rills along estate roads) and re-excavation and normal stream erosion of old ghauts was obvious. In the SE some geomorphic situations conducive to concentration and gullying are present, but the present vegetation will minimise the likelihood.

*Wind erosion.* Antigua and St. Kitts, although they do not have the combinations of weather, soil texture, and land use, like Barbuda, which are most conducive to wind erosion, nevertheless have several soils

which are conducive to wind erosion, but probably fewer occasions of suitable weather. In the aftermath of Lenny, no instances were mentioned, but perhaps in the coming dry season, there will be new evidence.

## Hazard maps produced

### 1 Deriving the maps

1 Simple empirical models, described earlier in the report were used to produce hazard scores for each land unit. The models integrate the estimated effects of elements of the environment which cause or influence the hazard and produce a score. The score is an estimate of the relative likelihood of the hazard at the land unit, but it has no physical meaning, like 'days per year' or 'tons per acre.'

2 To make the scores useable, they have been classified. For each individual hazard estimate, the scores have been divided into 5 equal area classes (20-percentiles, representing very low, low, medium, high and very high groupings), using the frequency distribution of the scores. Since the distribution of these hazard scores is usually "L-shaped" rather than uniform or "normal", the range of values in each class group is not uniform, (eg: 0-3; 3-17; 17- 62; etc). The advantage of the equal area classes over classes based on equal score intervals (eg: 0-100; 100-200; etc) is that we do not exaggerate the meaning of very high scores and the classes are relatively robust, in the face of minor errors.

3 If we try to combine the effect of different types of hazard we are faced with the problem of adding apples and pears, and we have no common element like calorific value to use. Adding scores for land units would produce some odd results, but adding classes reduces this problem, rather like standardising data. Composite maps were produced by adding classes and then reclassifying.

### 2 Choosing the most appropriate classes for defining land-based erosion hazard for development sites

Erosion hazards are most commonly defined in relation to open land either under agricultural use or intended for an agricultural use. The application to development sites, where some kind of construction is intended, is related to localised incidents rather than a general picture. This emphasises the need for data at a more appropriate scale, not available at present.

The effects of *sheet and rill* erosion are in most cases minimal in disturbing a building development site. In particular circumstances, *gullying* can be dangerous particularly where the site lies in the path of a gully working back inland from a stream or ghaut (eroding head wards). The problem of deposition of materials from sheet and rill erosion is of low impact, with some inconvenience which can be mitigated but little possibility of damage. Overall, rill and sheet erosion should be given little importance in assessing possible impacts on building development sites, while gullying is important.

The natural evolution of *streams* means that bank erosion is inevitable without canalisation of the stream course, and high likelihood of bank erosion is related to increases in rainfall, changes in the rapidity of runoff, and the conformation of the stream course. Predictions about rainfall are not very practical, but increased runoff can be predicted reasonably accurately in relation to land use changes. The erosion of stream banks and deposition of materials carried by the streams should only affect a small area adjacent to the existing stream course, but there could be instances where a new course is cut, replacing the lowest parts of a stream course. This particular effect is possible in the Antigua lowlands but highly unlikely in St. Kitts, where most likely some straightening or revision of bends may occur. Data was not available in an adequate form for making an estimate for Antigua and awaits a topographic map at about 1: 20 000 scale. Overall the stream bank erosion / stream adjustment effect could be important for development sites.

*Wind* erosion, although it can cause problems in certain circumstances, is unlikely to affect a building site seriously at the levels at which it is probable in the present circumstances of the islands, with the exception of Barbuda, where it might cause problems and other types of erosion are of less importance.

*Mass movement*, on the other hand, both the site from which the movement takes place and for the destination of material, can produce major difficulties for building development. Although no good examples of damage come to mind in the target islands, evidence from the Windwards is abundant of structural damage and loss of life. In St. Kitts, at present, the most obvious danger comes from the road cut through brecciated lava rocks leading from Basseterre to the southeast, and in Antigua and Barbuda from coastal cliffs in limestone, and some inland limestone cliffs, also from volcanic in the southwest or west of Antigua.

Consequently the chosen mapping combines gullying and mass movement (landslides and rock falls) and, where possible, an indicator of the probability of stream bank erosion. This is done by adding together the land unit by land unit values for gullying and mass movement and in the case of St. Kitts, indicating separately those catchments in which stream bank erosion is highly likely. For Barbuda alone, with a generally lower level of hazard, wind erosion is included. It should be noted that in the recent past in Barbuda, more damage was caused to soil, vegetation and some buildings by incursion of the sea, than by events originating on land.

## 3 Individual hazard maps and composite maps presented

The four final maps (one each for Antigua and Barbuda, one and a supplementary for St. Kitts), are composites, derived from the whole set of individual "erosion" process maps for each island. The full set, shown below, also available as larger maps, comprises:

### Antigua

Composite A: Composite hazard of gullying and landslides. (The hazards of sheet and rill erosion and of wind erosion in Antigua are not considered of great importance in relation to building development sites)

1 Rill erosion, bare soil, hazard classes:
2 Landslide overall hazard classes:
3 Wind erosion hazard classes:
4 Gully hazard (an overlay on 1, Rill etc):

### Barbuda

Composite A: Composite hazards of wind erosion and rock falls / debris slides. (The hazards of sheet and rill erosion and of gully erosion in Barbuda are minimal but wind erosion is relatively important and may provide a building development hazard)

1 Rill erosion, bare soil, hazard classes:
2 Wind erosion hazard:
3 Barbuda rock fall hazard is not mapped separately, Gully erosion hazard is near zero

### St. Kitts

Composites: A Composite erosion hazard classes (gullying and landslide / rock fall hazard of bare soil areas except in the area of the Forest Reserve, where the hazard under vegetation is taken). B Stream bank erosion hazard, to be used as an annotation to map (Wind erosion and sheet and rill erosion are not considered of importance in building development in St. Kitts.)

1 Landslides in the absence of cover, classes
2 Stream bank erosion hazard classes:

3 Hazard of rill erosion in absence of cover, classes
4 Hazard of rill erosion under land cover, classes
5 Hazard of wind erosion under land cover, classes
6 Hazard of gullying (overlay to bare soil rill), classes

## Discussion of results of the mapping

### 1 Electronic map production

Superimposition of thematic maps is the basis for calculating the hazard. The superimposition is not perfect, because several of the data source maps were:

- older thematic maps drawn on a base of unknown / uncertain origin
- drawn on unstable paper
- obviously different in their coastlines

Redrawing onto a standard base presents the possibility of greater error and in the case of both Antigua and Barbuda was impracticable, suitable base maps were unavailable. But the error, which is apparent at some coastlines, is well within the uncertainty zone of the thematic mapping.

### 2 Modelling of aspects of inland erosion:

*Inter- island and intra-island comparisons:* Barbuda vs. Antigua—justifiable; St. Kitts vs. Antigua/Barbuda—unsuitable, not justifiable

The modelling was carried out with intra-state comparisons in view. Comparisons between the results for different **states** would require revision of the K erodibility factors for individual soils and some of the mass movement ratings, because they are estimates of the relative values within the island soil group and not absolute values. The barrier to comparability occurs because the group of materials involved in St. Kitts is very different in its characteristics from the group in Antigua and Barbuda while the Barbuda materials fall readily within the limestone subgroup of Antigua materials. Further, because the variety of materials and other erosion-controlling factors is very limited in Barbuda, the number of different "scores" is relatively small. In this case the importance of the size of the differences in Barbuda erosion "scores" is better explained by showing how they would be placed within the Antigua table of "scores" than by using the very limited Barbuda table.

*Rainfall-induced erosion and deposition: sheet erosion; rilling; gullying.*

Rainfall-induced erosion affects soils and other little- indurated / soft materials, weak rocks etc. Erosion is the detachment of particles of materials and their transport away. It has a counterpart, deposition, where the transporting medium, water can no longer carry the load. Both effects can provide a major problem for cultivation, but neither is usually the cause of more than marginal inconvenience to urban areas. Gullying can be a major nuisance in rural areas but its effects are usually confined to open land. The lower ends of some gullies might reach development sites, but it is more likely that the "headward" erosion of gullies, for example those debouching on deeply cut ghauts, may approach the site. On the whole, in the states concerned, only gullying should present the possibility of more than a minor nuisance to development sites.

*Erosion of stream banks, development of new stream courses*

Stream courses: the cut (the bed) maintains equilibrium with the annual major flow—which may or may not be an actual over-the-bank flood. Where there is a flow much greater than the normal annual peak, bank

erosion can be expected and in some circumstances new courses may be cut. This may be important for some development sites.

*Landslides and rock falls– mass movement*

Landslides and rock falls are part of the normal processes of landscape development, but human activity often greatly increases their frequency and size. Road cuts, for example, which are routed through less stable materials often trigger landslides which continue for many years until a stable slope is achieved. The susceptibility of land to mass movements is very important for development sites. There are several areas of each island where rock falls are likely or easily induced. Deep landslides are possible in St. Kitts and shallow landslides are widely probable in St. Kitts and parts of Antigua.

## 3 Relative importance in the models of various different factors:

**Table Some factors used in the "inland erosion " assessment**

| Factor | Type of variable | Low value | High value | Ratio | Distribution of values [1] | Actual, field distribution [2] | Mapped approximation [3] |
|---|---|---|---|---|---|---|---|
| Soil (rainfall) erodibility K | constant | 5 | 46 | 10 | rectangular | ~ discrete units | discrete units |
| Soil (wind )erodibility I | constant | 11 | 66 | 6 | near square | ~ discrete units | discrete units |
| Slope angle | constant | 0 | 57.6 | ¥ | "L" shape | continuous | discrete classes |
| Rainfall intensity | temporal variable | 150 | 750 | | Left-skewed normal | continuous | discrete classes |
| Land cover | human control | 0 | 60 | 6000 | irregular | ~ discrete units | discrete units |
| Erosion control | human control | | | 10 | irregular | ~ discrete units | discrete units |
| Landslide susceptibility | artificial | 1 | 4 | 4 | - | discrete units | discrete units |
| Infiltration reduction | human control | 10 | 100 | 10 | Left-skewed normal | discrete units | discrete units |
| Streamsinuosity | artificial ratio | 1 | 1.5 | 1.5 | "L" shape | artificial ratio | discrete units |

Note 1 Frequency distribution: number of observations of each class or score

2 Discrete units, uniform areas, such as a single rock type. Continuous, varying continuously over the whole island

3 Discrete units, delineated areas with a single value, or discrete classes, continuous variable with isopleths ("contours") delineated

## 4 Sensitivity to change or error and significance of the different factors

The table above gives some indication of the relative importance of different factors in producing an answer. If land cover is excluded, and we think only in terms of the bare surface, the most important factor in water erosion and also in landslide susceptibility is slope angle. For islands like the Windwards and Leewards, soil erodibility is not much more than equal to rainfall intensity because of the wide ranges of rainfall in the islands, whereas in the areas for which most research has been done, soil erodibility is the key factor.

The table does not of course give any indication of the accuracy of the estimation for any particular point or area, but it does give an impression of the error in the calculation of the estimate which can come from the generalisation of slopes. It also shows that the difference from the low end of a class of a continuous variable mapped in discrete classes (rainfall intensity, e.g.) may mean a more than 20 % error in the calculation. Since the field records from which these continuous data are extrapolated are few and of uncertain accuracy, this only emphasises further that, although this is an estimate where relative hazard is probably reasonably well established, field confirmation of the points of interest is worthwhile. And more accurate determination using better data will reduce the amount of such checking needed.

Above all it confirms how very important is the land cover in determining water erosion hazard in particular, and landslide hazard susceptibility to a lesser degree.

**Climate and weather, variability and change**

The quantity of information on intra-island climate and weather differences is small and probably not very accurate. With climatic change in progress, knowledge of the existing range of variation may seem less important, but we still need to use the present upper limits of variation to estimate what the future may hold. Providing that there is no intra-island variation in the forthcoming changes our present classification of relative effects should remain good, but if we wish to make accurate physical estimates we shall need a better base for prediction.

**Land use, degradation and change**

It is clear that under natural forests and to a lesser extent other natural vegetation, sheet and rill erosion is relatively minor, and that mass movements are smaller and probably less frequent. Land use change to extensive agriculture using chemical weed killers and fire "improved" grazing produces lands which are devoid of natural protection. Without the provision of appropriate conservation measures, these contribute almost as much as ill-planned construction to the instability hazards. The present land use maps are very much simplified, so that the factors applied to the hazard over large units need to be reconsidered when information for a specific point is required.

## Conclusions and Recommendations

### 1 Data collection and recording. Basic simple research. Data needs

A recurrent problem throughout the Lesser Antilles, with the exception of the French islands, is a paucity of data for most basic environmental characteristics ("baseline data") and especially for some aspects of weather and climate, which are necessary for many kinds of research. There have been repeated attempts to set up weather observation systems, under the aegis of several different organisations, but all have failed because other priorities have prevailed. When predictions of the sort we have been contracted to make are required, this usually means that we are unable to use the most appropriate models, with real data. The consequence is the need to use information of the following kinds, which may not be good enough, especially in detail, although it will provide guidance:

- surrogate data—related by some process to the desired data, but often not directly related
- analogue data, from the French islands for example, which now very costly and can never fully substitute, or
- subjective estimates, which may sometimes provide as good an answer as any, but can never be checked or improved because of the lack of an explicit model

There is no solution to this problem without some investment of time and money by some organisation, and it may be that the time is ripe for a non governmental organisation (NGO) to be involved, rather than the

government service, where priorities change with the persons in power. It may be appropriate for a donor to offer a subsidy to an NGO prepared to commit to, for example, detailed weather observation, since virtually all attempts to make records adequate for agricultural research and land use planning / hazard management have failed.

Our studies were a first approximation (or "quick and dirty", to use a somewhat pejorative description). They represent all that can be done without both the collection of more detailed weather data over a period—a year would be helpful for some wind and rainfall intensities—and a real mapping of land use and land surface changes.

## 2 Revision of present information

The above discussion leads to a proposal that the basic information used now in the models should be revised at an early date. The question always asked is "why invest money in observations when we have to deal with the circumstances whether or not they are predicted?" One answer is simply that when the questions are asked, as they are being asked now, they cannot be answered adequately, and the basis for planning, avoiding calamities or mitigating ill effects, is poor or absent. A second answer is that we need not only to know what is present but also the rates of change. Our time horizons are very short and we rarely comprehend the actual magnitude of environmental change over periods longer than a few years. With climatic change obviously in progress, this is even more important since extrapolation from known data is likely to give us a much more realistic approach to the nature of change than a mere understanding that ill-effects will increase.

It is proposed that, in each of Antigua and St. Kitts:

- at least one weather station is set up, preferably on an existing well-documented site other than the airport, to obtain data which includes diurnal variation using autographic records for the main climatic elements and supports some, five perhaps, automatic weather stations in differing zones
- a land use survey is carried out in sufficient detail to distinguish differing kinds of agricultural and other extra-urban use
- a sample survey of the soils is conducted to establish physical normals and determine the amount of change that has taken place in 40 years since the earlier UWI (University of the West Indies) surveys
- quick surveys are made along existing roads in areas of highest landslide / rock fall hazard in Antigua and St. Kitts to pinpoint specific locations where landslides or rock falls are highly likely– possibly even imminent, so that monitoring and warning can be effected

These studies could well be carried out by local NGOs in association with UWI, and the costs should be modest, since a good deal of work can be carried out by volunteers paid only their expenses.

## 3 Perception of the erosion related hazards

In Antigua, local perception of the hazard, as expressed to the consultant during fieldwork, concentrated on the landslides in the higher steep lands, and on the reworking of stream courses, which have been barely running in the recent past, with damage to structures which were unwisely placed in or across valleys or stream courses. The high probability of a major earthquake and the landslides which will be related to it were not mentioned (and are ignored in the Environmental Profile).

In St. Kitts, the rock falls along the main road to the SE peninsula, long regarded as inevitable, seem to excite little interest, again according to the consultant's informants, but minor reworking of ghauts causes concern. Sheetwash accumulations on the downslope roads and below bare patches show recent effects in weather of only moderate erosivity, but are commonplace and disregarded. In Antigua the less obvious (after some time for vegetative cover) sheetwash and rilling were also not a matter for comment.

In both states the objects of concern are the more obvious, immediate and effectively inevitable problems, where any danger can be and is best mitigated by avoidance through the application of common-sense Town and Country planning. The more insidious effects of gullying, and to a lesser extent sheetwash, which are rather low-key but controllable by appropriate land management, are not on the agenda, even though overcoming their cumulative effects is greatly more costly, requiring widespread investment, if it can be effected at all.

In the rather different environment of Barbuda, the effects of sea incursion were more notable than any other erosion feature, but rock falls on the edge of and in the highlands are important hazards, with wind erosion always apparent, but probably never a major problem.

## 4 Mitigation - summary

The state of agriculture in Antigua is rather poor and much land appears to be abandoned, which may permit more surface cover and reduce sheet erosion, which was rather common. In most of St. Kitts the sugar cane is still dominant and it provides as effective an erosion control as is likely, but where it gives way to smallholder mixed cultivations, erosion is not under control. However the sugar industry is under notice of closure which means that great care needs to be given to the future of the sugar lands which will be much at hazard if bared. The dry lands of the SE peninsula are now largely given over to residential developments, and the remaining land appears to be in rough grazing, but not overgrazed.

In both islands attention needs to be paid to land use management. Farmers may or may not need to be instructed in conservation, but a little more investment in ensuring that good conservation practices are employed is necessary, both to minimise loss of fertility and the problems created by sedimentation.

However, since more concern was expressed over reworking of stream banks, and natural excavation of stream courses by the stream in spate, it is important to point out that building roads across an occasional stream without providing adequate culverts and permitting house construction within a gully (which is what St. Kitts ghauts really are) or on the edge of vertical stream banks in weak materials is not good practice.

Mitigation of earthquake induced rock falls and landslides also requires more careful recognition of potential recipient sites during Town and Country planning.

## 5 Mitigation-specifics

*Mitigation of water erosion: sheet erosion, rilling, gullying*

*1 Plan adequate drainage systems*
*2 Take action in response to land use change*

The main problem with dealing with water erosion is the effecting of changes in land use without appropriate conservation measures being taken. For example, where a piece of land under bush is converted to dwelling house lots, a marked reduction in infiltration—the way water enters the soil—and a marked increase in runoff results. The surface drainage of the area needs to be considered and linked to existing drainage in such a way that the drains will meet the flows produced by storms under the changed land use. This is a matter where planners need to enforce some rules. The second problem relates to the design of drainage systems in general. There are obvious examples in Antigua of drainage systems which do not lead anywhere and these need some thought. They may be effective during low intensity storms, in arresting flows and allowing delayed entry of water into subsoil, but they need outlets when larger intensity storms occur, or they will make their own, new, gullies, with probable damage to infrastructure. Drainage systems which do not cover a whole sub-catchment, and do not integrate all factors can cause as much trouble, or more, than no system at all. Drainage systems need to be planned to deal with a whole sub-catchment. And, although no particular problems were evident during field visits, except the case of the road to the southeast peninsula in St. Kitts often mentioned previously, the alignment and construction of roads and particularly

the provision for road drainage can provide long term instability problems and have been the initiator of major landslides and gullying throughout the Windwards. Again, this is a matter of planning, in which the planners need to ensure that developers including Public Works and farmers have given the matter adequate consideration.

Mitigation measures can cover probable erosion damage from rainfall based events only to a limited extent. To provide cover for the five hundred or thousand year return period storm requires building and maintaining drains and structures which, for long periods, would appear to be redundant. It is doubtful whether it could ever be supported. The recent extreme event in Antigua was obviously a very rare event, reaching an intensity rarely exceeded anywhere and is, unlikely to be experienced again in several lifetimes. But, with the current warming of the atmosphere and its multiplying effect on storm frequency and intensity we need to take rather more heed than formerly of events which appear to be 'extreme' using current data. If the warming continues we will need to revise opinions of the size of the storm we need to prepare for.

There is no lack of knowledge within departments of the various island governments of the means—planning, the specific conservation measures—by which mitigation of rainfall induced erosion can be effected. It is simply the case that for want of urgency, it is being neglected. The major problem (worldwide) is the fact that tree vegetation, natural forest especially, is being removed. The effect of the difference between forest cover and no cover is an increase in water erosion potential of at least six thousand times. Say six tonnes instead of one kilo. While we continue to make surfaces that erode easily, mitigation is a poor second best. Reafforestation of abandoned lands is something that can provide profit and environmental benefits.

*Mitigation of problems produced by wind erosion*

*1 Retain windbreaks, avoid large areas of exposed soil, use vegetation strips*

Wind erosion is only serious where literally bare soil is exposed to strong wind. The serious examples in Europe and N America ("dust-bowls") have occurred where large expanses of soil have been completely bare. In Europe, areas which had grown grains in fairly small fields without real problems were badly damaged by wind after the removal of hedges. Here any form of strip cultivation (provided it is not continuous over long distances, so as to provide a tunnel) should be effective. This is problem for agriculturists to tackle but one which will affect others, so planners should be involved.

*Mitigation of mass movement induced problems*

*1 Monitor and avoid areas at hazard*
*2 Provide cut-off drains*
*3 Use stabilising techniques (a costly last resort)*

Mass movement under gravity is not something which can be easily stopped. Some land use practices increase the hazard of mass movement—removal of trees and loading weak slopes (with buildings or roads) for example—and should be proscribed as a matter of common sense, since we all have to pay for the resulting damage. Building sites on or in the recipient area of such movements, should be discouraged, and would normally be a matter for rejection where Environmental Impact Assessments (EIA) are required. Once again planners should be able to minimise problems.

Rock falls, simply a movement of loosened lumps of material under gravity, can only be mitigated by:

- minimising damage:
- quarantining the predicted receiving site altogether
  - identification and regular monitoring of potential falls, and provision of a catch site or barricade if that appears likely to be cost effective
  - terracing. This is costly and not particularly effective or appropriate where a vertical cut has higher land behind

- -minimising the likelihood of a fall:
  - identification and artificial protection —such as sealing cracks where infiltrating water may remove some material or assist slipping

Débris slides, rotational shear slides in clays, etc (and some rock falls ) may be mitigated by:

- -minimising the likelihood of a slide:
- reducing lubrication to the slide by cutting ditches above the likely slide site to carry water away from the slide plane
- avoiding loss of tree cover from such a site
- -minimising damage:
  - monitoring likely areas and minimising use

Mitigation of problems caused by stream bank erosion / stream reworking / new courses

1 *Keep drainage ways clean of impediments– do not fill with solid waste etc*
2 *Avoid using potentially endangered land for permanent structures*
3 *Use structures to deflect damage to sites or reduce reworking effects (a costly last resort)*

Stream courses can be canalised, as they often are where they pass through towns. However, to prevent the adjustments which are natural processes of stream development will often be unreasonably expensive elsewhere and sometimes very difficult, as I believe it would be in most cases in St. Kitts. It might be less difficult in Antigua but would still be costly and rarely giving a beneficial return commensurate with cost. The task is for planners to provide the right information.

These problems can really only be mitigated for the long term by:
- avoiding the likely sites of reworking which are easily predictable from channel shape
- canalisation of a long stretch of the stream— this is not likely to be cost effective in St. Kitts, except perhaps downtown, but might be in some cases in Antigua
- finding a means of reducing maximum flows (e.g. dams)

Temporary protection can be effected by:
- providing walls supporting the attacked site
- baffles, deflecting the stream flow

But it is unlikely that these will be cost effective except in a few instances.

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