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Headwater deforestation: a challenge for environmental management

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Abstract

Headwaters are the zero-to-first-order catchments that form the upstream margins of all river basins. Environmental changes in headwaters, not least deforestation, can affect the quantity and quality of the water resources downstream. Headwater control is a philosophy that strives to link the perspectives of the applied scientist with the practitioner and policy maker. It emphasises practical, field scale, action research and integrated environmental management strategies that work within nature and with local communities. In Slovakia, Central Europe, where economic transition has affected forest management, measurements of sediments in 27 small headwater reservoirs showed a negative correlation with the degree of forest cover. In Honduras, Central America, where forest conversion is caused by the agricultural colonisation of very steep slopes, accelerated sediment production is not constrained by conventional cross-slope barriers of *Vetiveria zizanioides* (vetiver grass). Assailed by Hurricane *Mitch*, the steepest (65–75%) slopes became source areas for landslides that removed around 600 times more sediment than that removed annually by surface wash, producing sediments that buried fields and choked water courses down-slope. The grass barriers did little to prevent landslide generation, but deep-rooted trees might have been more effective. Achieving sustainability in such environments will require a longer term perspective on the significance of environmental extremes and the dangers of building reliance on structures that halt only smaller range events.
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1. Introduction

The Millennium Development Goals of the United Nations (UN) Millennium Declaration (UN General Assembly Resolution 55/2) grant a key role to forests (World Bank Group, 2000). Forest cover has been adopted as a key environmental stability indicator (UNFF Secretary General, 2003). Forest resources contribute to the livelihoods of 90% of those now living in poverty (World Bank Group, 2002, p. 9). Forests play a vital role in the sustainability of clean and reliable water supplies and in the mitigation of the accelerated sediment release that clog reservoirs and exacerbate floods. According to the World Bank Group (2002, p. 20), during the 1990s, forests were lost at the rate of 15–17 million ha yr^{-1}, with some nations losing 2–3% of their cover each year; this contributed to almost 20% of global greenhouse emissions and, in the topics and subtropics, to soil losses equivalent to 10% of agricultural gross domestic product (GDP). In some high-income and transition economy countries rural depopulation has allowed forests to recover, and there have been small gains elsewhere, but across the board, the pressure on the global forest is increasing (UNFF Secretary General, 2003). There are many underlying causes but development and forest conversion in head-water regions is a major source of the problem (Haigh, 1999; Verolme and Moussa, 1999).

Headwaters are the places where water flow-lines originate and where much groundwater recharge occurs. They are the highest grounds in every river basin and the ultimate source of much fresh water. They are important because, when water qualities and yields change in headwaters, the consequences affect the lands down-stream (Tognetti, 2000). The finite and vital nature of freshwater resources has long raised concern regarding the socio-economic, political and environmental security of human activities and ecosystem health in watersheds. The Millennium Development Goals also include commitments to improving water security and

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environmental sustainability, adding that better integrated natural resource management increases social welfare and reduces the risk of disaster from floods, while improved water quality improves health and reduces child mortality (World Bank Group, 2000). The World Summit on Sustainable Development (WSSD) also gave such themes high priority. They lie at the heart of the Water and Sanitation, Energy, Health, Agriculture and Biodiversity (WEHAB) initiative. Its frameworks for 'Action on Water and Sanitation' and for 'Action on Agriculture' highlight the role of agriculture in deforestation and water pollution (WSSD, 2002). In many landscapes, headwater uplands provide the last redoubt for forests and they are the areas most strongly affected by forest conversion.

In 1989, the 'Headwater Control Movement' came into existence to focus attention on the practical problems of improving the recognition and management of environmental change in headwater uplands (Krecek et al., 1989). Subsequently, the movement has sought, especially at the field scale, to promote better environmental understanding through empirical research, the development of improved strategies for environmental reconstruction and conservation through action research, and the design of better environmental management structures (Van Haveren, 2000; Haigh et al., 1998; Krecek and Haigh, 2000). Its key to better environmental management is the creation of integrated management institutions that are controlled by the local communities of the headwater areas but that respect the needs of all stakeholders (Van Haveren, 2000). This message has evolved through six major international meetings, most recently one co-sponsored by the United Nations University (UNU) in Nairobi, Kenya, where it was finally proposed that the movement were better titled 'Headwater Self-Control'.

In the process, the movement has gained some insights into the effects of environmental change and the limits of environmental technology at the point where they intersect with human activities, especially with regard to deforestation, sedimentation and flooding. This work is illustrated here by a case study of reservoir sedimentation in Central Europe, specifically Slovakia's Western Carpathian headwaters. The Headwater Control Movement has sought also to expand recognition that some activities, which currently pass as environmental protection, actually increase human misery in extreme conditions; and it is that unproven increase in extreme climatic conditions that would be the most persuasive harbinger of global environmental change (Lovelock, 1991). This paper illustrates this through an examination of an extreme event, the impact in 1998 of Hurricane *Mitch* on steep hillsides, arguably protected by soil conservation structures, in the headwaters of southern Honduras in Central America.

2. What are 'headwaters'?

Headwaters are, by definition, lands at the margins of hydrological systems but they often provide the margins of other environmental and social systems. They are first- to zero-order catchments, the places 'where rivers are born', all rivers, large and small (Krecek and Haigh, 2000). At the Joint Research Centre of the European Union (EU), a pioneering study by Paracchini et al. (2000) found that headwaters occupy between 41% and 58% of the total EU area (3,220,000 km^2), while 12% is mountainous and 46–65% forested. A very large proportion of the land surface lies between each water divide and the first stream channel of the hydrographic network.

Creating this statistic, of course, was a very interesting process. Headwaters share the fractal characteristics of the river channel network. Every steam and river basin has headwaters. Headwaters are found at the extremities of large international river basins; equally they provide the margins of every tributary and sub-catchment within the basin. The area that may be classed as headwater depends, to a great degree, on the scale of the inquiry.

This EU study used two methods for its continental scale inventory (Paracchini et al., 2000, pp. 69–73). Both employed digital elevation models based on GTOPO30 (United States Geological Survey) and used a threshold value of 1 km^2 (1 cell). This work was qualified by detailed case studies based on digitised maps of higher resolution. The team extracted the river network and calculated stream orders (Strahler method). In Method 1, they calculated the source areas (pour points) for all first-order streams. In Method 2, they evaluated the area above the first intersection of two first-order streams. Both methods identified more than 550,000 headwater areas in the EU (Paracchini et al., 2000, p. 75).

This study has not been replicated elsewhere but, intuitively, results are likely to be similar in other regions of the world. Paracchini et al. (2000) also note that, en masse, the EUs headwater areas are distributed uniformly across a wide altitudinal range. By definition, headwaters provide the highest lands of each and every river catchment, but only some are in mountains.

The most critical feature of a headwater system, one that they all share, is that they are upstream margins and that everywhere else in their drainage basin is downstream of them. In the case of the world's headwater regions, environmental change provides a major threat to the lives and livelihoods, not merely of the residents of those areas, but also to those downstream who are affected by changes in the quality and quantity of water and other resource streams from these areas (Tognetti, 2000). Viewed on the scale of nations, many headwaters lie in the front-line of development for agriculture, forest farming, mining, tourism, nature preservation, hydroelectric power and water supply. Many also lie on the margins of national and regional socio-economic systems while some contain political boundaries between rival social, cultural and military groups.

Traditionally, such headwaters are associated with low levels of human occupation, isolation from major industrial and economic processes, and relatively high levels of forestation. In post-socialist societies, economic transition has often entailed a massive restructuring of both economy and society, sometimes with harmful consequences—especially in marginal headwater regions (Zlatic et al., 2003). In some areas, while the problems of transboundary air pollution may be in decline, changing social values and systems of environmental protection, not least for forests, have led to new problems. These concerns lie at the heart of the first case study of reservoir sedimentation rates in Slovakia in Central Europe.

In developing societies, many steepland forest headwaters have experienced recent colonisation by smallholder farmers who have been displaced from better quality agricultural lands. In such communities, the struggle for immediate survival has higher priority than any concern for the future or the surrounding environment, even where the skills and resources needed for its management exist. In such cases, the problems of environmental degradation rarely remain in the headwaters. Regions downstream suffer through water and sediment pollution, changes in the hydrological regime, and reduced natural resource supply, which may also lead to social stress and livelihood disruption (Haigh et al., 1998). This topic is illustrated by the second case study from the deforested, tropical, steep lands of southern Honduras in Central America. However, this case also demonstrates why the proper management of headwater resources has become one of the most significant challenges for environmental management and development.

3. Case study—sediment pollution of small reservoirs in the headwaters of the Western Carpathians, Slovakia

The headwater regions of the Western Carpathians are part of the Danube Basin, one of three major European rivers that drain a quarter of the continent. The Danube passes through mountain gateways, agricultural plains, wetlands and several nations but, throughout, deterioration of water quality limits the use of its surface waters (Molnar, 1994). From a hydrological perspective, the Danube is characterised by major changes in the volume and movement of sediment, channel deepening, increased meandering and frequent floods.

The World Lake Vision report argues that accelerated erosion is producing sediments that degrade water quality in lacustrine ecosystems (ILEC and UNEP, 2003). The European Soil Resources Report notes that the harmful off-site effects of water erosion present serious problems across Europe (Van Lynden, 1995). In recent years, there has been an increase in forest conversion and other land disturbances in Slovakia's Western Carpathian headwaters. Since the onset of transition, the forestry sector in several nations has faced severe difficulties because of reduced financial and other support from current governments and because of the restitution of lands to, often inexperienced, private owners. Sustainable forest resource management and many other aspects of natural resources management presently suffer from neglect.

Slovakia's small water reservoirs serve many useful functions: improving the total water balance within their catchments, mitigating floods, fostering biodiversity, enabling pisciculture and recreation as well as providing water for many uses, most especially the irrigation of local agricultural crops. Official standards define small water reservoirs as basins with a capacity of not more than 2 million m^3 of water, a maximum depth of 9 m and a hundred-year peak discharge no greater than $60\,m^3 s^{-1}$. Nationally, there are around 350 such small water reservoirs, including 193 that are administered by the Slovak Ministry of Agriculture, and these are used mainly for supplementary irrigation. Together, they have a surface area of 1910 ha and a design capacity of over 45 million m^3.

However, sedimentation is rapidly reducing both their volume and useful life-times. It is also causing the deterioration of water quality, obstruction of reservoir flow regulation structures, reduction of flood control capability, and the degradation of environment quality (e.g. providing more breeding areas for mosquitoes and reducing the reservoirs' recreational value). The sedimentation of small water reservoirs has become a national concern across Slovakia and the problem is especially severe in headwater uplands.

Traditionally, the problem has been countered directly. Each year—if funding is available—perhaps 3 out of 193 reservoirs are emptied and the accumulated sediments removed. However, this is, increasingly, a very expensive operation and also unequal to the scale of the problem. It would be far better if the supply of sediment to the reservoirs were reduced so that clearance was required less frequently. With this aim, an investigation was launched to determine the controls of sedimentation in these sub-mountainous small water reservoirs.

3.1. *Method of study*

The Slovakian Small Water Reservoirs Project measured and analysed data from 27 reservoirs and their catchments. Situated at altitudes between 135 and 380 m, these 27 reservoirs have storage capacities that range from 17,000 to 288,000 m^3, maximum water surface areas from 1 to 20 ha and average depths between 0.69 and 2.54 m. Catchment areas average 11.2 km^2 (range: 0.8–28.0 km^2) and support 0–60% forest cover, of mostly altitudinal 1–2 zone forest-types, of *Ulmeto-Fraxinetum (Ufr)*, *Carpineto-Quercetum (CQ)* and *Fageto-Quercetum (FQ)*.

The relatively small size of the target reservoirs made the direct measurement of sedimentation in emptied reservoirs a viable, if work-intensive, option. Records were collected by regular grid sampling. The volume of sediment between cross-sections of the reservoir were calculated as the average of the sediment in cross-sectional area times the distance between cross-sections, then summed over the total area. Where possible, sediment depths were verified by direct coring. However, in a few cases, where part of the basin remained submerged, sediment depths had to be estimated (Jansky and Kvasnica, 1987; Jansky, 1992).

3.2. Results

The data showed that the amount of sedimentation ranges from 4.8% to 83.6% of total storage capacity. Deposition effects an annual decrease in storage volume of 0.32–9.30% against an anticipated design-life of 100 years. To counter this, maintenance clearance would be required, on average, every 15 years (see Table 1).

From the catchment perspective, these sedimentation rates imply annual sediment yields between 10.4 and 442.4 $m^3 km^{-2}$. Certainly, many environmental factors affect sediment release. Nevertheless, a significant regression may be calculated between reservoir sediment accumulations and the deforested area in these watersheds (Fig. 1). In this regression analysis, a quadratic function provided the best-fit between total non-forested watershed area and volume of sediment accumulated in the reservoir (Jansky, 1992; Fulajtar and Jansky, 2001).

3.3. Discussion

The case study indicated that the continuing reduction of forest cover in small watersheds may accelerate sediment release and degrade the capacities of small storage reservoirs through sediment deposition (cf. ILEC and UNEP, 2003). This reduces the reservoirs' capacities to provide irrigation waters to meet the needs of local farms, so reducing their productive capacity and economic effectiveness. Since the same sedimentation also affects irrigation canals, pumping stations, and

Table 1
Summary of the reservoir and headwater regions' sedimentation data for the Middle Danube River Basin in Europe (Western Carpathian Mountains) (Janksy, 1992; Fulajtar and Jansky, 2001)

Reservoir	Sub-Basin	Reservoir watershed area (km^2)	Reservoir flooded area (ha)	Reservoir capacity ($10^3 m^3$)	Non-forested watershed area (km^2)	Average annual sediment accumulation (m^3)
1. Pl. Vozokany	Hron	20.1	17	164	18.09	7 554
2. Veľký Ďúr	Hron	10.2	10	130	10.20	3 762
3. Drženice	Hron	17.5	7	98	12.25	3 676
4. Mankovce	Nitra	18.0	3	50	9.00	188
5. Kolíňany	Nitra	17.0	13	106	15.30	1 474
6. Čápor	Nitra	13.1	8	128	13.10	556
7. Jelenec	Nitra	11.1	7	174	5.55	1 861
8. Bajtava	Hron	5.5	7	48	4.95	721
9. Dedinka	Hron	16.4	15	246	14.76	4 326
10. Dubník	Hron	12.5	14	240	12.50	2 360
11. Maňa	Nitra	6.2	8	169	6.20	960
12. Trávnica II.	Nitra	25.3	20	288	20.24	7 478
13. Svodín	Hron	9.8	14	221	9.80	4 171
14. Brezolupy	Nitra	24.0	7	90	9.60	3 143
15. Nedašovce	Nitra	28.0	6	60	14.00	1 174
16. Rátka	Ipel'	0.8	1	17	0.48	250
17. Bolešov	Váh	11.1	2	26	4.44	544
18. Glabušovce	Ipel'	8.7	14	180	6.96	580
19. Karná	Bodrog	2.0	2	17	1.20	578
20. Košic. Olšany	Hornád	3.5	2	25	2.80	505
21. Pol'ov	Hornád	5.1	5	75	5.10	971
22. Trstená pri H	Hornád	8.4	2	34	5.88	864
23. V. Kamenica	Bodrog	11.4	2	32	7.98	2 972
24. Gem. Teplica	Slaná	3.7	14	257	2.22	1 067
25. Hrušov I.	Slaná	2.6	4	36	1.82	1 150
26. Nižný Žipov	Bodrog	3.5	9	146	3.50	1 270
27. Bor-Továrne	Bodrog	7.5	8	203	3.75	1 464

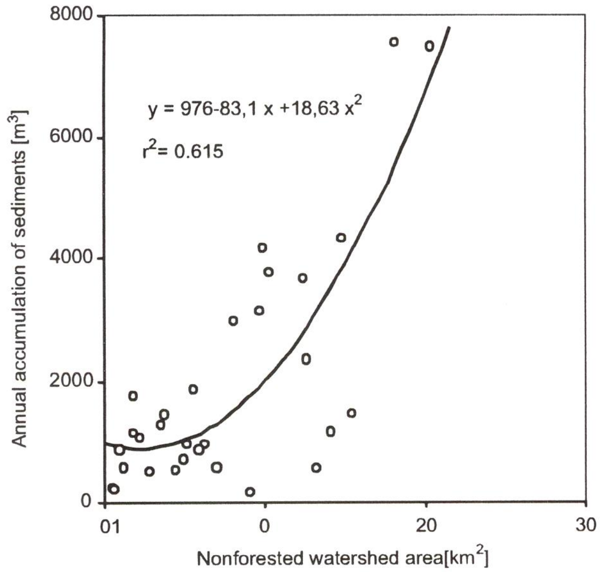

Fig. 1. Relationship between sediment accumulations (m^3) in small water reservoirs and non-forested area in Slovakia's Western Carpathian headwaters (Fulajtar and Jansky, 2001).

river training works, making these less capable of dealing with extreme hydrological conditions, it may be inferred that flooding may also become a more common problem in affected basins.

4. Case study—soil conservation protection of steep hillsides in Honduras and the impacts of Hurricane Mitch

In the tropics and subtropics, as pressures on the land increase, the challenge is to sustain and improve the land's productivity without destroying its quality (Bridges et al., 2001). In the front-line of this struggle are steep lands (defined as land with a gradient greater than 20%), where economically disadvantaged farmers are bringing fragile and erodible lands into cultivation (Stocking and Murnaghan, 2001). An increasing proportion of agricultural land conversion in the tropics involves steep slopes and the result is accelerated erosion and soil degradation (El-Swaify, 1994; El-Ashry, 1988; Hudson, 1988). In Central America, soil degradation may affect 75% of all agricultural land (cf. World: 21%) (Bridges et al., 2001).

Land degradation is caused by poor land husbandry and unsustainable agricultural practices. In many parts of the developing world, the increase in poor land husbandry is consequent upon the displacement of smallholder farmers from fields in the flat-lands by the advance of modern commercial agriculture (Myers, 1993). Displaced farmers who do not migrate to the cities, often move to the margins, colonising steep land in unfamiliar terrain in headwater regions. Frequently, such land has remained uncultivated because of its poor qualities.

Steeply sloping lands are fragile geoecological systems, susceptible to rapid soil degradation due to physical, chemical and biological processes (Lal, 1988). Steep land is much more vulnerable to water erosion than flat land because the erosive forces of gravity and running water all have greater effect as slope angle increases. This represents a most formidable obstacle to effective agricultural development in headwater areas. Small miscalculations may have dramatic consequences and any ill-advised cultivation may cause severe erosion. Despite this, research into agriculture on slopes greater than 20%, has been neglected because the cultivation of these sites is considered inappropriate and unsustainable (Lal, 1988).

Research problems are compounded because these new agricultural headwater steep lands may be remote, difficult to access and extremely variable in landscape and natural events (Hudson, 1992, p. 145). Further, it is not easy to extrapolate research results from shallow slopes, because the processes affecting steep slopes differ in character and degree; the relative differences in proportion between, for example, erosion through surface wash and that through soil creep or mass movement are not well established (El-Swaify, 1997). A lack of field experience provides the strongest technical limitation to attempts to promote agricultural sustainability in these contexts (El-Swaify, 1994). This second case study details a project designed to provide some understanding of the practical implications of subsistence farming on steep slopes and the value of some typical soil conservation measures both for soil/sediment release and for agriculture production (Hellin and Haigh, 2002a).

4.1. Methods

A series of test plots were set-up on steep slopes at Santa Rosa, near the city of Choluteca, in the headwaters of southern Honduras. The aim of the project was to evaluate the effects of a typical soil conservation technique, cross-slope live barriers of *Vetiveria zizanioides* (vetiver grass), on soil and water losses and maize production (Greenfield, 1989). The plots were unusual in only one respect: although they were located on the margins of an official research station, they were cultivated by local farmers, who agreed to receive the crops produced in exchange for the facilitation of data collection (Hellin and Haigh, 2002a).

The research involved 24 field-scale (24 m × 5 m) test plots on two hill slopes (slope angles: 35–45% and 65–75%). Each set of test plots received two treatments, maize cultivated with and without interspersed live-barriers at 6-m spacing. Each test was replicated six times in a randomised sequence across the two test slopes. Data collection involved the use of eight continuously recording water/sediment samplers and passive collection in lined catch-pits (Hudson, 1995, p. 173–175; Sombatpanit et al., 1992). The experiment was conducted over three years and five maize harvests from 1996 to 1998. However, research was abruptly terminated in October 1998 by Hurricane Mitch, which also largely destroyed the sixth and final maize harvest of the study (Hellin and Haigh, 2002a). The full results of this study are being prepared for monographic publication (Hellin, 2004).

4.2. Results

In 1996, total soil loss per plot ranged from 9.8 to 41.8 t ha^{-1}; in 1997 from 0.5 to 4.8 t ha^{-1} and in pre-Mitch 1998 from 0.7 to 1.8 t ha^{-1}. Low soil losses in 1997 and 1998 (pre-Mitch) were linked to low rainfall, the *El Niño* effect, and more ground cover in 1998. Overall, the average annual soil loss by erosion for the steep slopes was around 17 t ha^{-1} (see Table 2 column 6). Pre-Mitch and against expectation, there were no significant differences between the volumes of soil collected at the slope foot from treated versus untreated slopes on either steep or more steeply sloping test plots. Furthermore, there were no significant differences in the volumes of soil collected at the foot of either the steep (35–45%) or steeper slopes (65–75%).

There were also no significant differences in maize production from treated versus untreated slopes on either steep or more steeply sloping test plots, except in one of the two cropping seasons in the dry *El Niño* year of 1997. On this occasion, there were significantly higher yields from the plots that were protected by cross-slope barriers of vetiver grass. The reason seems to have been that, even in the few years of the cropping cycle, these barriers had caused soil to accumulate upslope and diminish immediately down-slope, transforming the hillside into a series of small steps. Normally, this had no impact on average crop yields. However, in the exceptionally dry year of 1997, the greater depth of soil up-slope also allowed greater water retention. This was sufficient to allow a net increase in crop yields on barrier protected slopes (Hellin and Haigh, 2002b).

4.3. Hurricane Mitch

Undoubtedly, many aspects of these findings are affected by climatic variability. In 1996, there was 3037 mm of rainfall. In 1997, the *El Niño* effect allowed only 1614 mm. In 1998, much of the 3175 mm recorded rainfall total was due to Hurricane Mitch. This struck Central America towards the end of October 1998. Between 1800 on 27 October and 2100 on 31 October 1998, there was 896 mm of rainfall (Hellin et al., 1999) (Local Time = GMT −6 h). In the three periods of extreme intensity: 186 mm fell during the 6 h 1600–2200 on 29 October, 74 mm fell during the 4 h 0100–0500 on 30 October, and 254 mm fell during the 6 h 1600–2200 on 30 October. Maximum rainfall intensities ranged from 138 mm h^{-1} (2-min period) to 58.4 mm h^{-1} (60-min period) (Hellin et al., 1999).

As a consequence, downstream in Choluteca, the river burst its banks and shifted its course, flooding most of the city, obliterating several km^2 of secondary forest, suburban housing, and also a 200-m section of the main road on the city margin. Nearby, Morolica, a rural village of 3600 inhabitants vanished; 75% of the houses were washed away, but thanks to prompt community action, only 12 lives were lost.

However, in total, Mitch's floods and landslides claimed approximately 11,000 lives; it was the most deadly hurricane to strike the Western Hemisphere in 200 years (McCown et al., 1998). In Honduras, the United States Geological Survey estimate that 6600 persons were killed, 8052 injured, 1.4 million persons were left homeless and nearly 70% of crops were destroyed (Powers, 2001). Soon afterwards, the Choluteca River bed became a dust bowl: "Following massive floods that changed the river's course, a month's worth of dried mud, silt, chemical contaminants, human waste and remains are choking the air" (Herlinger, 1998).

Landslide activity was a major problem and source of sediment pollution. In southern Honduras, almost all the landslides occurred during the two periods of most intense rainfall on 29 and 30 October when, according to Mastin (2002, p. 19), the maximum daily rainfall at Choluteca was 465 mm against an estimated 50-year daily maximum of 303 mm. Observations made immediately after Mitch indicate that approximately 5% (but in some areas as much as 20% of the hillsides)

Table 2
Sediment yields from 65% to 75% slopes on the Honduras test plots (including landslide sediment production linked to Hurricane Mitch, October 1998) (Haigh and Hellin, 2001)

Area of slope	Total area of landslides	Volume soil removed by landslide	Soil loss from landslides	Soil loss from landslides (t ha^{-1})	Average annual loss by soil erosion (t ha^{-1})
10,500 m^2	3027 m^2	6983 m^3	10,460 t	9961	17

in southern Honduras suffered similar landslides (Haigh and Hellin, 2001, Barrance, 1998). Photographic records at Santa Rosa show a swarm of landslides and debris flows on the forested hills behind the research plots.

The trial site was also severely affected. Landslides destroyed 50% of the maize crop on the steep slopes (35–45%) and 75% of the maize crop on the steeper slopes (65–75%). Five deep-seated landslides formed on the steeper slopes where 1.5–2 m deep scars affected 70% of the test plot area. The depth of these landslides, of course, far exceeded that of the root-strengthened zone of either vetiver grass or the maize crop, although mature tree roots might have extended this deep. It was, therefore, no surprise to find control and live-barrier plots equally affected by landslides. No landslides originated on the 35–45% slopes. Here, most of the damage was caused by debris from landslides and surface soil movements originating on steeper slopes (> 50%) above and outside the research site. These source slopes had been cleared of secondary forest in 1997 and also planted with maize.

It was not just the test plots that were damaged; the disaster brought the scientific study to an abrupt halt. Recording apparatus designed to measure soil losses in terms of a few millimetres, and sediment losses in terms of a few kilograms, was completely destroyed by landslides that moved several metres of land surface and dumped several tonnes of debris. Only the autographic rain gauge worked perfectly throughout the entire event, a result that impressed even its manufacturers (Hellin et al., 1999).

Since Mitch destroyed the catch-pits and sediment samplers, no accurate figures exist for sediment yields during the hurricane. Instead, volumes of soil lost through landslides from the whole area (circa 1 ha) on the steeper (65–75%) slopes were calculated from photographs and measurements made at the trial site some 10 days after the hurricane struck. Following Herweg (1996, p. 50), the volume of soil removed by the five landslides was estimated by measuring the area covered by the landslides and multiplying this by the average depth of the landslide scar from measurements taken at different points (Table 2). On site measurements suggest an average soil bulk density of just under 1.5 t m^3. This figure can be used to convert the volume of soil removed (m^3) into tonnes of sediment, and thence to t ha^{-1} (Table 2).

Table 2 indicates that the sediment yield from the landslides of October 1998 was approximately 600 times greater than the average annual soil loss caused by water erosion and cultivation on these same steep slopes.

4.4. Key questions

The huge difference between the rates of soil loss caused by the landslides and by 'normal' erosion processes on a steep slope, recently converted from forest to agriculture, raises some important questions. First, did the vetiver grass barriers really protect the steep slope plots from land degradation, or did they do no more than provide a false sense of security? Several authors argue that cross-slope soil conservation measures were effective during Hurricane Mitch. Reporting on an area close to Santa Rosa, Thurow (1998) writes "the cropped sites with vegetation contours, rock walls and tree fallows withstood the storm quite well, but sites that did not have these investments were devastated by massive landslides" and is quoted by the Vetiver Network (Bange, 1999).

A study of 1804 farms across Central America confirmed that farms using "sustainable" practices including soil and water conservation methods appeared to suffer less damage than their "conventional" neighbours (Holt-Gimenez, 2000, 2001). The study made paired observations of the ten best examples of sustainable farms in a given community and ten neighbouring conventional farms, which were located, in close proximity, with similar slopes and environmental contexts. Indicators measured included topsoil depth, rill and gully erosion, percent vegetation, crop losses and structural damage. The owners of both farms accompanied the team on both sustainable and conventional plots, and signed off the field record to show records were free of bias. Sustainable farms had fewer and smaller gullies and areas of rill erosion (Holt-Gimenez, 2000, 2001). However, on steep slopes (> 50%), under conditions of high storm intensity, the differences between sustainable and conventional farms vanished, indicating that these techniques have thresholds of effectiveness.

The research at Santa Rosa also indicates a slope-angle-related threshold. During Hurricane Mitch, landslides occurred only on the steeper slopes (65–75%)—the merely steep slopes (35–45%) received land slide debris but did not generate any landslides themselves. This result contrasts with the data from 1996 to 1998 (pre-Mitch) for soil loss caused by water erosion. In this case there were no significant differences between the steep (35–45%) and steeper (65–75%) slopes (Hellin, 1994).

Second, have the soil conservation works and other environmental management activities been targeting the correct problem? For example, if Hurricane Mitch is a 1-in-200 year event, then using the data in Table 2, landslides are a three times larger source of sediment loss than surface wash on steep agricultural hillsides. Even if Hurricane Mitch were a 1-in-500 year event, on the steepest (65–75%) slopes, landslides would still be the largest factor in sediment production. The defence against landslides should, therefore, be the fundamental concern of all soil conservation activities.

Table 3
Flood hazard estimates (m^3/s) for the Rio Choluteca en Puente Choluteca Gauge close to the Pan American Highway in Choluteca, Honduras (Kresch et al., 2002)

Peak Discharge during Hurricane Mitch—estimated from indirect measurements	15,500
Next highest measured flood peak on record	2130
50-year flood discharge estimated from the period of station record (1979 1998)	12,500
50-year flood discharge based on local historical information (56-years)	4910
50-year flood discharge estimate used for flood hazard mapping purposes	4613

The significance of this new problem has been highlighted by the advent of a United States Geological Survey led flood hazard mapping project conducted in response to Hurricane Mitch's impacts. These studies are coy about the possible recurrence interval of the hurricane, which, as the largest event in every hydrological data run—most of which do not achieve a total of 50-years—might be conceived as a <50-year event, or by extrapolation of the local records of historical flood peaks, a >50 or 200-year event (cf. Kresch et al., 2002; Mastin, 2002).

The United States National Oceanic and Atmospheric Administration (NOAA) calculates the risk of a hurricane striking Honduras's north coast in any one year as 1–2%, and the risk of one reaching Choluteca, very much less (Mastin, 2002, p. 5). However, the 50-year flood estimates of the United States Geological Survey team share the property that they are all a small fraction of the actual discharge experienced during Hurricane Mitch (Mastin, 2002, p. 27) (see Table 3). Indeed, the Mitch discharges cannot be fitted on the exceedance probability graph computed by the study (Kresch et al., 2002, p. 5).

No doubt, the process of flood hazard mapping could help local authorities resist the colonisation and development of the most vulnerable flood-plain areas. Unfortunately, it could also have the side-effect of encouraging both the development of the land immediately above the estimated 50-year flood level line and the popular understanding that such development was safe from flooding. It is hard to construct a false sense of security based on the data above. Unfortunately, flood hazard maps exude an air of authority and once they are printed, they become 'scientifically established' facts to many users.

5. Discussion

Today, there is concern at the highest level to foster development that is sustainable and to enhance the quality of the water resources available for human usage (WSSD, 2002; World Bank Group, 2000). Simultaneously, the environment is being transformed by human actions at an accelerating and unprecedented rate. Environmental managers face burgeoning change and massive challenges from advancing land degradation, which they do not have the resources to manage, at least at the necessary scale (Bridges et al., 2001).

Currently, theoretical, laboratory and computer-based, research is displacing applied, field and experience-based research in many nations. The works of the Headwater Control movement strive to provide a counter current that emphasises field level practical experience, common-sense action, and revalidation of the fundamentals of theoretical understanding. For example, the case study from Central Europe establishes, at national scale, the strong link between deforestation and accelerated reservoir sedimentation.

Forests are one of the most abiding features of Europe's headwaters. They are already considered among the most degraded in the world (UNFF Secretary General, 2003). Although they cover 30% of Europe's land, less than 2% may be classed as 'old growth forest' (UNFF Secretary General, 2003). These forests are threatened by a variety of factors, administrative changes resulting from the transition from Socialism, with all of its social and economic effects (cf. Zlatic et al., 2003), or more widely fires, road construction, tourist resort development, pollution, commercial exploitation and neglect (UNFF Secretary General, 2003). The Slovakian case study illustrates the top end of a chain reaction that begins with headwater deforestation, and leads through reservoir sedimentation, declining agricultural effectiveness, and beyond. Its cause is a breakdown in the administrative and economic structures that protected environmental security in the past. Its solution may lie in the creation of new, empowered, structures for integrated watershed management and sustainable development (cf. Van Haveren, 2000; Zlatic et al., 2003).

Social, economic and agricultural changes are also vital issues in the development of sustainable land husbandry in Central America (cf. Bunch, 1982; Verolme and Moussa, 1999; Hellin, 2004), but the Honduras case study described here reveals a different and serious technical problem. This concerns the capacity of present environmental technologies to cope, effectively, with the problems of environmental protection for sustainable development. Agricultural colonisation in the tropical world is affecting ever steeper slopes. This study suggests that some of the new land exceeds the capacities of some very common technologies, like vetiver live barriers, to defend the land against degradation—even in the short term. There was no significant difference in the sediment yields from live barrier protected and conventionally farmed land on either the steep (35–45%) or steeper (65–75%) test plots.

The essence of sustainability is that it looks to the long term but, in the context of the management of those headwaters where steepland development proceeds rapidly, the understanding of long-term processes is weak. This weakness was exposed by Mitch, which showed that cross-slope vetiver grass barriers could not defend the soils of the steepest (65–75%) slopes in hurricane conditions. It also showed that in the long term, on such slopes, the dominant form of soil loss, and greatest threat to the pollution of runoff and river courses, comes from landslides rather than the wash of surface soils. This, of course, implies a radically different approach to the design of cross-slope soil and moisture conservation barriers. It also suggests the importance of preserving some deep-rooting tree cover on such slopes.

Finally, subsequent experience also exposes the continuation of short-term thinking in environmental management. Table 3 shows the huge range in the estimations of the '50-year flood hazard' in southern Honduras (Kresch et al., 2002). However, rather than learning from Hurricane Mitch and attempting to shift vulnerable development to sites where an equivalent storm could do no damage, current planners will use a flood-hazard map that encourages development that will be vulnerable to a storm of less than one-third of Mitch's scale.

The situation illustrates a problem that is inherent in much engineering design thinking, such as the concept of the design storm. Some of the devices and structures that are created can accentuate the consequence of their exceedance. By protecting against small hazards, they soften up a vulnerable population, building a false sense of security, until exceedance occurs and the protection fails. If space permitted, this problem could have been illustrated further by a third case study from the Headwater Control archive. This involves results from a 5-yearly repeated record of landslide activity along a suburbanising highway in the Lesser Himalaya. Here, suburban development has altered the normal patterns of landslide activity. On the new suburban sections of the road, there are now far fewer small or medium sized landslides, due to the construction of drains and retaining walls. However, there are as many or more very large and catastrophic slope failures (cf. Haigh and Hellin, 2001).

6. Conclusion

Headwater control, as a movement, evolved from a desire to re-connect applied environmental science with the basic realities of practical field scale environmental management. Its aim remains to work with field practitioners, with field scientists, within natural systems and within the limits of the local land husbandry systems, towards the establishment of self-sustainability (Krecek and Haigh, 2000). Headwaters, zero-to-first-order catchments, provide the margins of all river basins and the sources for rivers. Environmental changes that affect the headwaters of a river basin can affect all those areas downstream (Tognetti, 2000).

Traditionally, at all scales, headwater uplands have been the least developed parts of most catchments but many now provide the front lines of development. Forests have been a characteristic feature of many headwaters and, in many environments, headwaters contain the last major forest reserves. However, today, some of these forests are being challenged by a wide array of development processes; their cover and extent is being reduced and the consequences of these changes are being felt (Haigh, 1999; Verholme and Moussa, 1999).

This paper has illustrated two aspects of headwater control in contrasting areas suffering forest conversion. The first concerns forest losses caused by transition in post-Socialist Central Europe. This study, of reservoir sedimentation in Slovakia's Western Carpathians, confirms the connection between forests and sediment yields. It also demonstrates the need for integrated watershed management and the problems that occur when headwaters are not managed by appropriate administrative structures.

The second case study concerns the impacts of agricultural colonisation on marginal steep lands in the tropics of Central America. It demonstrates the role of action research in discovering the limits of environmental management technology and the significance of long-term environmental variability. It indicates that one typical soil conservation technique, cross-slope live barriers of vetiver grass, may be ineffective for soil protection on the steepest slopes now being brought into cultivation. These grass barriers effected no significant reduction in soil losses on all test plots steeper than 35% and proved ineffective against landslide generation on the steepest slopes (65–75%). These results highlight the importance of the long-term perspective in planning for sustainability. The landslides induced by Hurricane Mitch removed as much soil as 600 years of surface erosion, yet landslides had been a minor factor in soil conservation thinking. Finally, this study illustrates the dangers of relying on technological defences. These may be effective against the smaller range environmental extremes but may also breed complacency and vulnerability to those greater extremes that exceed their design capacity.

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