Tropical Ecology **48**(2): 151-161, 2007 ISSN 0564-3295

www.tropecol.com

Land use change and its impact on hydro-ecological linkages in Himalayan watersheds

E. SHARMA[1*], S. BHUCHAR[1], MA XING[2] & B.P. KOTHYARI[3]

[1]*International Centre for Integrated Mountain Development, Khumaltar, P.O. Box 3226, Kathmandu, Nepal*
[2]*Kunming Institute of Botany, Chinese Academy of Sciences, Heilongtan, Kunming, P.R. China (650204)*
[3]*G.B. Pant Institute of Himalayan Environment and Development, Kosi-Katarmal, Almora, India*

Abstract : Mountains are amongst the most fragile environments in the world and are a repository of biodiversity, water and other ecosystem services. Mountains influence far more than their geographical limits and extend to the surrounding lowlands with the goods and services. The mountains are facing enormous pressures from various global change related driving forces including land use change. The land use change is happening in an unprecedented manner in the Himalaya. Five watersheds representing the middle mountains of the Himalaya were selected in China and India for understanding the hydro-ecological linkages of land use change. The natural forest decreased in both the countries with the highest change of 20% in Mamlay Watershed of India during 1988 to 1997 and simultaneously the area under open forests increased in most cases. In the Indian watersheds the agricultural land increased with the highest value of 16% recorded in the Mamlay watershed over a decade. The reverse trend was recorded in the Chinese watershed where the cropland and tea garden areas substantially reduced, however showing the increased plantation forest area by 38% during 1982-1998. Soil loss recorded in some of these watersheds ranged from 250-616 t km^{-2} yr^{-1}. The land use change transformed ecosystems, their functions especially the hydrological performances and impacts on ecosystem services were visible. Promotion of forests and agroforestry in combination of rehabilitation of degraded land in the mountain watersheds could improve land husbandry for providing hydrological benefits to both upstream and downstream users.

Resumen: Las montañas se encuentran entre los ecosistemas más frágiles del mundo y constituyen un reservorio de biodiversidad, agua y otros servicios ecosistémicos. La influencia de las montañas se extiende mucho más allá de sus límites geográficos y alcanza las planicies que las rodean con sus bienes y servicios. Las montañas están enfrentando presiones enormes de parte de varias fuerzas directrices relacionadas con el cambio global, incluyendo el cambio de uso del suelo. El cambio de uso del suelo está ocurriendo de una manera sin precedentes en los Himalaya. Se seleccionaron cinco cuencas representativas de la porción montañosa media de los Himalaya en China y la India, con el fin de entender las conexiones hidroecológicas del cambio de uso del suelo. El bosque natural decreció en ambos países y el cambio más fuerte (20%) ocurrió en la cuenca Mamlay de la India durante 1988 a 1997, y simultáneamente el área de bosques abiertos se incrementó en la mayoría de los casos. En un caso de las cuencas de la India la tierra agrícola se incrementó en alrededor de 16% en una década. En la cuenca china

* *Corresponding Author*; e-mail: esharma@icimod.org

se registró la tendencia inversa, donde la tierra de cultivo y las áreas de cultivo de té se redujeron sustancialmente, a pesar de lo cual se observó un incremento de 38% en el área forestal de las plantaciones durante 1982-1998. La pérdida de suelo registrada en algunas de estas cuencas fluctuó entre 250 y 616 t km^{-2} año^{-1}. El cambio de uso del suelo transformó los ecosistemas y sus funciones: particularmente visibles fueron los desempeños hidrológicos y los impactos en los servicios ecosistémicos. La promoción de los bosques y la agroforestería, junto con la rehabilitación de tierras degradadas en las cuencas montañosas, podrían mejorar el manejo del suelo para la provisión de beneficios hidrológicos a los usuarios ubicados tanto en las partes altas como en las bajas de la corriente..

Resumo: As montanhas encontram-se entre os ecossistemas mais frágeis do mundo e constituem um reservatório de biodiversidade, água e outros serviços ecossistémicos. A influência das montanhas estende-se muito para além dos seus limites geográficos e alcança as planícies ao seu redor com bens e serviços. As montanhas estão enfrentando pressões enormes por parte de várias forças incluindo as mudanças no uso da terra. A mudança no uso da terra está ocorrendo de uma forma sem precedentes nos Himalaias. Seleccionaram-se cinco bacias representativas da faixa montanhosa intermédia dos Himalaias, na China e na Índia, para compreender as relações hidro-ecológicas da mudança no uso do solo. A floresta natural diminuiu em ambos os países e a mudança mais elevada (20%) ocorreu na bacia de Mamlay, na Índia, no período de 1988 a 1997 e, simultaneamente, a área das matas abertas aumentou em ambos os casos. Num caso das bacias hidrográficas da Índia, o solo agricultado aumentou cerca de 16% numa década. Na bacia chinesa registou-se uma tendência inversa, onde o solo agricultado e as áreas de cultivo do chazeiro se reduziram substancialmente, tendo-se verificado um aumento da área florestal plantada da ordem dos 38% no período entre 1982-1998. A perda de solo em algumas destas bacias situou-se entre as 250-616 t km^{-2} ano^{-1}. A alteração no uso do solo transformou os ecossistemas e as suas funções e que são particularmente visíveis quanto aos desempenhos hidrológicos e aos impactos nos serviços proporcionados pelos ecossistemas. A promoção de plantações e da agrosilvicultura, em conjunto com a reabilitação das terras degradadas nas bacias montanhosas, podem melhorar o manejo do solo para proporcionar benefícios hidrológicos para os utentes quer a montante quer a jusante.

Key words: Forests, micro-watersheds, overland flow, precipitation partitioning, rainfed agriculture, runoff, soil loss.

Introduction

Mountains all the over the world, which cover one-fifth of the globe, are unique in their ecological systems, culture and economy. Half of the humanity is dependent in one way or another on mountain ecosystems. Sixty percent of the planet's fresh water comes from the mountains. The Hindu Kush-Himalayan (HKH) region is the highest mountain range in the world, and it extends about 3500 km from Afghanistan to China in east-west, and 250 to 300 km in north-south extension. It includes parts or all of the mountain areas of Afghanistan, Bangladesh, Bhutan, China, India, Myanmar, Nepal and Pakistan. The region directly sustains more than 150 million people, but the water basins count 1.5 billion inhabitants, and up to 3 billion people live from food and energy produced by the Himalayan rivers (Schild 2007).

The region is geologically very young. The main uplift including the evolution of the Indo-Gangetic basin is dated to the late Tertiary/early Quaternary (about 1.7-1.5 million) years before the present (Valdiya 1998). The topography of the Himalaya is unique. Over a distance of only about 170 km there is a relief from about 80 m asl in the Gangetic plains to more than 7000 m asl (Merz 2004). The prevailing farming systems in the HKH are: rice-wheat; integrated irrigated rice, wheat, vegetables, and livestock on the southern boundary of the HKH and the inner valleys of the middle mountains; followed by highland mixed farming systems incorporating a range of cereals, legumes, tubers, fodder, and livestock (Dixon *et al.* 2001). Large areas of high altitude areas are pastoral with and sparely located agriculture. On the upper slopes (above 3000 m) farming depends on potatoes and buckwheat, as well as cattle, sheep and yak.

The HKH region is the largest storehouse of fresh water in the lower latitudes (Chalise 2000). Mighty rivers such as the Indus, the Ganges, the Yarlung-Tsangpo, the Brahmaputra, the Nu-Salween, the Yangtze, the Yellow River and the Mekong, which are life line for lower areas, originate in this region. The HKH region is also home to many rare and endangered species, and provides an important migration corridor for wildlife (Chettri *et al.* 2007). This beautiful region's extreme topography, climate, remoteness and tectogenesis make it instable, fragile and vulnerable resulting in high rate of soil erosion. The Himalayan rivers rank amongst the top rivers in terms of suspended sediment load (Meybeck & Ragu 1995). Rivers originating from Central Himalaya show the highest values of more than 65 t ha^{-1} $year^{-1}$, however, the western Himalayan rivers show low sediment delivery rate of below 15 t ha^{-1} $year^{-1}$ (Lauterburg 1993).

The land use change, population dynamics and climate change are the main drivers of environmental change. These drivers have changed the livelihoods of the mountain people, and increased their economic and environmental vulnerabilities dramatically. The sources of these drivers are both internal and external to the HKH region. And they mutually reinforce the effects they have on human wellbeing, and natural resources availability and use. While mountain people are particularly vulnerable to such changes it is immediately less apparent but nonetheless true that these changes impact entire river basins and eventually also globally.

The land use/cover changes from forest to other uses have been widespread in the past several decades in the Himalayan region (Rai *et al.* 1994; Singh *et al.* 1983). Such changes in land use/cover lead to environmental degradation through soil erosion and nutrient loss. Agricultural land area has increased considerably over the past four decades in the Himalaya at the costs of other land uses, particularly forests (Sharma *et al.* 1992). The forest-dominated watersheds are consequently converted into agrarian watersheds where sediment and nutrient losses are accelerated. Understanding the relationship between land use/cover and hydrology is critical to the prediction of soil fertility, nutrient budgets and local water recharges for the functioning of watersheds. This paper analyses the land use/cover changes and their hydro-ecological linkages for integrated management of natural resources in the five middle hill watersheds of the Himalaya.

Table 1. Physiography of the selected Himalayan watersheds.

Physiography	Watersheds				
	Bhetagad	Xizhuang	Khecheopalri	Khanikhola	Mamlay
Area (ha)	2354	3456	1209	416	3014
Elevation range (m)	1090-2060	1700-3075	1700-2375	300-1700	300-2650
Average rainfall (mm yr^{-1})	1291	1382	3638	1200	2000
Climate	Sharp wet and dry seasonal variations	Wet and dry seasonal variation	Wet seasons	Wet and dry seasonal variation	Wet and dry seasonal variation
Major cash crops	Winter vegetables, Fruit, Tea, Fodder	Tea, Tobacco, Fruits and Potato	Cardamom	Orange and Vegetables	Cardamom, Orange, Ginger and Potato
Staple crops	Mixed cereal grain, Paddy and Wheat	Maize, Wheat, Beans and Paddy	Maize and Millets	Maize, Pulses and Millets	Pulses, Maize, Millet and Paddy
Forest area (%)	56	75	84	12	50

The study watersheds

Five watersheds studied, reviewed and discussed in this paper represent the conditions of the middle mountains all over the Himalaya. The physiographic characteristics including major cash crops, staple crops and forest areas of these watersheds are presented in Table 1. The selected watersheds (Khanikhola, Khecheopalri, Mamlay, Bhetagad and Xizhuang) are in monsoonal and wet areas of the Himalaya in India and China.

The Khanikhola watershed lies in Sikkim (India), which is an agrarian with about 50% area under rainfed agriculture. There is a strong traditional agroforestry base in the watershed, broadly classified into three types: (1) large cardamom (*Amomum subulatum*); (2) mandarin; and (3) tree-fodder based systems. The National Watershed Development Programme for Rainfed Area carried out interventions for increasing economic benefits to the farmers, and in-depth studies on soil, water and nutrient conservation in this watershed have been made by Sharma *et al.* (2001).

The second watershed is also located in the state of Sikkim called as the Khecheopalri watershed. The significance of this watershed is the presence of a "Wish Fulfilling Lake" considered by the Sikkimese people as most scared. The lake is used for rites and rituals only. The lake is situated in the midst of a pristine forest and it represents the original 'neve' region of an ancient hanging glacier (Raina 1966). The lake is a resting place for trans-migratory Himalayan birds and supports recreational and commercial tourism (Jain *et al.* 1999).

The Mamlay watershed is located in southern district of Sikkim. It is quite similar to the Khanikhola watershed in its characteristics. It is also agriculture dominated watershed having practices of traditional agroforestry systems. Detailed studies on hydrology and nutrient flux of this watershed are available (Rai & Sharma 1998a; Sharma 2003). The watershed lies entirely in the mountainous zones bearing evidences of two persistent thrusts, the Sikkip and the Tendong (Sharma *et al.* 1992).

The other two watersheds, namely the Bhetagad and the Xizhuang, are located in the Indian Central Himalaya and in the western part of Yunnan Province in China, respectively. The Bhetagad watershed has a sub-tropical to temperate climate with three pronounced seasons of summer, monsoon, and winter. Chir pine (*Pinus roxburghii*) is the predominant conifer species in the watershed and accounts for 56% of total forest cover in the watershed (Bisht & Kothyari 2001). The Xizhuang watershed also has a subtropical to temperate climate. The main soil type is red and the natural vegetation is semi-moist broadleaf forest that disappeared many decades ago and has been replaced by coniferous forest with a mixture of Himalayan alder (Jianchu *et al.* 2005). Long-term hydrometerological, on-farm and farming systems research was carried out in these watersheds under the "People and Resource Dynamics in Mountain Watersheds of the Hindu Kush-Himalayas", which was coordinated by International Centre for Integrated Mountain Development in collaboration with G.B. Pant Institute of Himalayan Environment and Development, Kunming Institute of Botany and Centre for Biodiversity and Indigenous Knowledge.

Land use/cover change

Conversion of forests to other forms of land management has been the general trend in mountainous areas. Such land-use change has been conspicuous over the past several decades in the Himalayan region (Rai *et al.* 1994). Forest-dominated watersheds are converted into agrarian watersheds. This type of conversion has been necessitated by increasing population pressure and limitation of productive agricultural land (Rai & Sharma 1998b). The goal of forested watershed management is thus the rational utilization of land and water resources for optimal production with minimal disturbance to natural resources (Sundriyal *et al.* 1994). The land management in the catchments and watersheds of mountainous region like the Himalaya essentially relates to the ecosystem services that they provide to the mountain people and downstream populations. Such ecosystem services essentially relates to soil and water conservation by proper land-use, protecting from deterioration of soil quality, increasing and maintaining soil fertility, reducing soil erosion, conserving water for drinking and other farm uses, increasing the availability of basic resources and achieving the optimum productivity of land-uses (Sharma *et al.* 1992). The soil without tree cover on steep upland farming systems such as associated with more intensive agricultural practices is vulnerable to soil erosion and reduced soil fertility (Rai & Sharma 1995). The recent challenges confronting sustainable development is linked to such large scale land use degradation and transition for meeting the growing demands for food and other services. As a result majority of the populations depending on forests and tree resources for their subsistence have become vulnerable.

The land use pattern of the Bhetagad watershed in 1996 was pine forests (56%) and rainfed agriculture (42%). The major land cover changes from 1963 to 1996 were expansion of the agriculture area and settlements by conversion of forest area (Table 2). Similarly in Khecheopalri and Mamlay watersheds forests have decreased from 12 to 20% while showing increase in agriculture land by 10 to 16%. The khecheopalri watershed being remotely located showed land cover change of the above mentioned magnitude to happen in 34 years while the Mamlay watershed located near the urban center faced the situation in just 13 years (Table 2). In contrary to the Indian watersheds, the Xizhuang watershed in China showed the opposite trend of land cover changes. The grassland and rainfed agriculture land reduced while the forest cover increased by 38% in just 16 years between 1982 and 1998. The majority of land conversion into forests resulted by increased areas under plantation forests after the supportive policy for private forestry during 1990s in China.

Precipitation partitioning, overland flow and soil loss

Partitioning of incident precipitation into various pathways in natural forests and cardamom agroforestry in Khecheopalri and Mamlay watersheds is presented in Table 3. In Khecheopalri watershed; through-fall was 72%, canopy interception 25%, floor interception 50% and floor leachate 23% in the forests, while the through-fall was 59%, canopy interception 40%, floor interception 21% and floor leachate 37% in the cardamom agroforestry. Similarly in Mamlay watershed; through-fall was 80%, canopy interception 10%, floor interception 43% and floor leachate 47% in the forests, while the through-fall was 55%, canopy interception 41%, floor interception 41% and floor leachate 18% in the cardamom agroforestry (Table 3). Stem-flow and

Table 2. Land use/cover change in various watersheds in the Himalayan region.

Watershed / Land use	Year and Area (%)		Change Period (years) and Area (%)
Bhetagad Watershed (Uttarakhand, India)	1963	1996	33
Forests	60.65	55.58	- 5.07
Rainfed agriculture	34.97	42.34	+ 7.37
Wasteland areas	3.63	1.32	- 2.32
Others	0.75	0.76	+ 0.01
Xizhuang Watershed (Yunnan, China)	1982	1998	16
Forests/bushes	36.80	75.10	+ 38.30
Pasture/grassland	29.20	0.30	- 28.90
Rainfed agriculture	32.90	22.50	- 10.40
Others	1.10	2.10	+ 1.00
Khecheopalri Watershed (Sikkim, India)	1963	1997	34
Forests	95.90	84.20	- 11.70
Rainfed agriculture	3.20	13.40	+ 10.20
Others (lake and bog areas)	0.90	2.40	+ 1.50
Mamlay Watershed (Sikkim, India)	1988	1997	13
Forests	69.70	49.90	- 19.80
Agroforestry (cardamom & mandarin)	3.86	3.86	0
Rainfed agriculture	14.40	30.30	+ 15.90
Others (wastelands)	11.30	15.20	+ 3.90

Table 3. Precipitation partitioning in forests and agroforestry systems of Khecheopalri lake watershed and Mamlay watershed in Sikkim, India.

Partition components	Khecheopalri Watershed (Study year 1997-1998)		Mamlay Watershed (Study year 1994-1995)	
	Forests	Cardamom agroforestry	Forests	Cardamom agroforestry
Incident precipitation (mm)	3638	3638	1482	1482
Through fall (mm)	2615	2131	1190	816
Stem flow (mm)	109	47	147	57
Canopy interception (mm)	914	1460	145	609
Floor interception (mm)	1804	769	644	608
Floor leachate (mm)	854	1359	693	265
Biomass incorporation (mm)	0.63	0.52	0.94	0.53

Source: Rai & Sharma (1998a); and Jain *et al.* (2000)

biomass incorporation was significant and showed similar trend of slightly higher values in forests than cardamom agroforestry. Although the through-fall in agroforestry system is lower compared to forests, the canopy and floor interceptions and floor leachate in agroforestry systems balances the pathways contributing to ground water recharge by reduced overland flow. The results of the precipitation partitioning show that much of the natural forests pathway functioning are retained in cardamom agroforestry. This study is supported by the reports on positive relationship of interception with canopy cover in the central Himalayan oak forests (Pathak *et al.* 1983). Waring *et al.* (1980) argued that the surface area of the forest is an important determinant in interception processes which is also observed in cardamom agroforestry systems in the present study. Rai & Sharma (1998b) have also shown that the nutrients are mobilized on leaf surface, stem bark and floor litter in the precipitation partitioning thereby affecting the nutrient dynamics within the land use systems.

Average annual precipitation in the five watersheds ranged from 1200 to 3638 mm (Table 1). Most of the watersheds received moderate precipitation except for the Khecheopalri receiving high rainfall. Percentage of average runoff compared to the total annual precipitation was 1-10% in Bhetagad, 2-5% in Khecheopalri, 3-9% in Khanikhola and 3-11% in Mamlay watershed (Table 4). In the case of Bhetagad watershed rainfed agriculture showed the lowest runoff with a contrast of high values for pine forests. However, in Khecheopalri and Mamlay watersheds both forests and cardamom agroforestry proved to be more efficient in water conservation with reduced percentage of the runoff. The cardamom agroforestry when compared in the three Sikkim watersheds showed that the runoff in Khanikhola

Table 4. Annual runoff and soil erosion from the study watersheds.

Land use	Average runoff (mm)	Soil loss (t km^{-2} $year^{-1}$)
Bhetagad Watershed		
Pine forests	134	270
Rainfed agriculture and tea plantation	18	85
Degraded land	71	260
Xizhuang Watershed		
Forests	-	7
Rainfed agriculture area	-	460
Pasture	-	8
Khecheopalri Watershed		
Forests	79	640
Cardamom agroforestry	69	120
Rainfed agriculture area	145	2842
Degraded land	183	1990
Khanikhola Watershed		
Forests	83	300
Cardamom agroforestry	109	390
Rainfed agriculture area	59	2160
Wasteland areas	34	170
Mamlay watershed		
Forests	84	220
Cardamom agroforestry	84	180
Rainfed agriculture	224	1006
Wasteland areas	50	250

was higher attributed by lower density and sparsely shading species; in Khecheopalri and Mamlay the dominant shade tree was *Alnus nepalensis* while in Khanikhola it was *Albizia stipulata*.

Average soil loss in the different watersheds ranged from 205-1398 t km^{-2} $year^{-1}$ which varied between 85-270 t km^{-2} $year^{-1}$ in Bhetagad, 7-460 t km^{-2} $year^{-1}$ in Xizhuang, 120-2842 t km^{-2} $year^{-1}$ in Khecheopalri, 170-2160 t km^{-2} $year^{-1}$ in Khanikhola, and 180-1006 t km^{-2} $year^{-1}$ in Mamlay watershed (Table 4). In Bhetagad watershed soil loss from rainfed agricultural land was lower and in contrary both the wasteland and pine forests showed greater loss which is mainly attributable to open grazing and disturbed situation in latter land uses. In the other four watersheds the rainfed agriculture showed the highest soil loss ranging from 460 t km^{-2} $year^{-1}$ in Xizhuang watershed in China to 2842 t km^{-2} $year^{-1}$ in Khecheopalri watershed in Sikkim of India (Table 4).

The total area in hectares and per cent coverage of different land uses of the Mamlay watershed categorized into forests and wastelands, agroforestry systems, rainfed agriculture and total watershed are presented in Table 5. Overland flow, soil loss and nutrient loss through eroded soil from total area of each land use and the entire watershed were estimated. The overland flow was highest from rainfed agriculture and lowest from agroforestry systems. The total flow from the watershed was 2288x10^6 l while the soil loss was 600 t $year^{-1}$. The highest soil loss of 586 t $year^{-1}$ was recorded in the rainfed agriculture and the rest 14 t $year^{-1}$ was shared by forests and agroforestry systems. Soil loss from both forests and agroforestry systems are relatively very low compared to rainfed agriculture in wet and monsoonal areas like Sikkim. Total nitrogen, organic carbon and total phosphorus loss through eroded soil was mainly contributed by rainfed agriculture amounting to more than 95% for all nutrients and remaining 5% of nutrient loss was observed from forests and agroforestry systems (Table 5). The forested land use or the agroforestry systems show high water retention, soil and nutrient conservation by the land use systems.

Soil loss from micro-watersheds within the Mamlay watershed and total for the entire watershed was estimated using discharge and sediment load. The Mamlay watershed which drained out from the Rinjikhola represented the

Table 5. Overland flow, soil and nutrient loss in the Mamlay watershed (values are based on six rainfall events).

Land use	Area		Overland flow (x10^6 l)	Soil loss (t for six rainfall events)	Nutrient loss through eroded soil (kg for six rainfall events)		
	(ha)	(%)			Total nitrogen	Organic carbon	Total phosphorus
Forests and wasteland areas	1552	51	325	8	63	318	7
Agroforestry systems	142	5	55	6	71	415	5
Rainfed agriculture areas	1320	44	1908	586	2901	14705	836
Total watershed	3014	-	2288	600	3035	15438	848

Table 6. Soil loss estimated using discharge and sediment load in micro- and total-watersheds in Mamlay, Sikkim, India.

Micro-watersheds	Area (km^2)	Soil loss (t km^{-2})	Total soil loss (t $year^{-1}$)
Pokcheykhola	7.88	145	1142
Chemcheykhola	7.17	124	888
Tirikhola	5.10	408	2080
Sombarykhola	6.35	69	435
Rang-Rangkhola	3.64	90	328
Rinjikhola*	30.14	616	18578

*It represents the total watershed values and this stream forms the watershed outlet.

watershed values covering 30.14 km^2 and the micro-watersheds were Pokcheykhola, Chemcheykhola, Tirikhola, Sombarykhola and Rang-Rangkhola with area ranging from 3.64 to 7.88 km^2 (Table 6). Soil loss from different micro-watersheds ranged from lowest value of 69 t km^{-2} in Sombaryhkola and the highest value of 408 t km^{-2} in Tirikhola. The discharge, sediment load and soil loss from the micro-watershed was dependent on the land use and management systems. The Trikhola micro-watershed which contributed greatest soil loss was dominated by rainfed agriculture while the Sombarykhola micro-watershed showing minimum soil loss was under forests and agroforestry as dominant land management systems. The total soil loss from the watershed outlet through Rinjikhola estimated by discharge and sediment load showed 18578 t year^{-1} from the entire watershed with 616 t km^{-2} year^{-1}. Similarly Bhetagad watershed in the Central Himalaya which received relatively less precipitation compared to Sikkim in the Eastern Himalaya with an area of 23.5 km^2 showed total soil loss from the watershed as 8366 t year^{-1} averaging 356 t km^{-2} year^{-1} (Table 7). The average soil loss per kilometer square in the Mamlay watershed is double than that of Bhetagad watershed which received half the amount of precipitation, this clearly shows that soil loss is also related to volume of precipitation.

Land-use impacts on hydrological parameters and sediment transport are inversely related to the spatial scale (Table 8). Beneficiaries who would like to have good quality water, better biodiversity services, better climate and aesthetic values for recreation and ecotourism, and for the hydropower energy producers, who want less sediment, the options like good quality forest combined with improved traditional agroforestry are promising and need promotion. These options would certainly work best in “normal circumstances”. If there are big rainfall events, large scale gully erosion and mass wasting can be the sources of sediment and erosion flooding in small catchments (Hudson

Table 7. Annual rainfall, runoff and soil loss in Bhetagad watershed sub-catchments. The values are means of three years.

Sub-catchment (SC)	Rainfall (mm)	Runoff (x 10^6 l)	Soil loss (t km^{-2})	Soil loss (t year^{-1})
SC-1 [1.1km^2 area; forest 20% and agriculture 69%]	1103	290	188	207
SC-2 [1.7 km^2 area; forest 22% and agriculture 64%]	1073	460	346	588
SC-3 [2.6km^2 area; forest 48% and agriculture 45%]	1073	750	286	744
SC-4 [23.5 km^2 area; forest 42% and agriculture 49%]	1072	8190	356	8366

Source: Verma & Kothyari (2005)

Table 8. Impact of land-use changes at different scales on various hydrological parameters.

Impact	Basin size (km^2)						
	0.1	1	10	100	1000	10,000	100,000
Average flow	√	√	√	√	-	-	-
Peak flow	√	√	√	√	-	-	-
Base flow	√	√	√	√	-	-	-
Groundwater recharge	√	√	√	√	-	-	-
Sediment load	√	√	√	√	-	-	-
Nutrients	√	√	√	√	√	-	-
Organic matter	√	√	√	√	-	-	-
Pathogens	√	√	√	-	-	-	-
Salinity	√	√	√	√	√	√	√
Pesticides	√	√	√	√	√	√	√
Heavy metals	√	√	√	√	√	√	√
Thermal regime	√	√	-	-	-	-	-

Source: FAO (2002)

1995). Merz *et al.* (2003) reported a suspended sediment yield of 0.9 - 1.8 t ha^{-1} yr^{-1} for the Wang Basin; the most important river for hydropower generation in Bhutan.

Conclusions

The five middle hill watersheds studied presents a major human habitation zone in the Himalaya. These watersheds represent both forested and agrarian types where the land use/cover and their differential ecological and hydrological linkages were analyzed. Broadly the major proportion of the land cover can be categorized into forests, rainfed agriculture and agroforestry systems. The study was objectively divided into four sets of components of land use transformation and hydrological cycle, (i) land use/cover change, (ii) overland flow and contaminant soil loss rates under different types of land management, (iii) precipitation partitioning into various pathways in forests and agroforestry systems, and (iv) sediment loss in micro-watersheds. The catchments draining into a particularly stream in the watersheds particularly in the Mamlay watershed comprised of various land use practices and there was no uniform land use for a stream. This attribute in diversified land use management is a unique feature for watersheds in the Himalaya that adds to the complexity of the hydrological functions.

Conspicuous changes in the land use/cover were observed in the five watersheds of the Himalayan region, and the impact on the hydro-ecological systems was both positive and negative. Of all the watersheds only in the Xizhunag watershed, the rainfed agricultural land and tea gardens decreased resulting into increased area under forests. This forest recovery was attributed to forest promoting Sloping Upland Conversion Programme of China launched on a large scale mitigation response to the massive floods in the Yangtze river in 1998. The programme, however, has been detrimental to the local livelihoods as it has reduced the opportunity for farmers to grow enough crops and at the same time limited the access to forest resources (Jianchu *et al.* 2005).

The overland flow, soil loss, nutrient loss from soil erosion and precipitation partitioning are the hydrological functions impacted by different land use systems. The overland flow, and soil and nutrient loss were greatest in rainfed agriculture in most of the watersheds except for the Bhetagad watershed in the Central Himalaya. In most of the watersheds the rainfed agriculture land are degraded because of regular loss of soil and nutrient affecting soil fertility and productivity of land use systems. The results for the overland flow, soil and nutrient loss, and precipitation partitioning in different pathways in natural forests and agroforestry systems suggest that these land uses promote conservation of soil, water and nutrients. It is seen that the forests provide hydrological and ecological benefits to the upstream and downstream communities by providing regulating functions, while the agroforestry systems adds the provisioning functions. Therefore, in land management systems forests should be conserved in much of the areas and the recent trend of conversion of forests into other land use should be reversed. However, for meeting the ever increasing demand of land for cultivation in the mountains the conversion of forests cannot be avoided which could be favourably transformed into good agroforestry systems that provide both regulatory and provisioning functionality.

The studied watershed provided situations at both micro to meso-scales. Sustenance of watershed functioning in the mountains needs substantial support from outside including downstream, and this can be operationlized by various approaches and one of them could be payment for environmental services. Promotion of forests and agroforestry practices in combination with rehabilitation of degraded lands and better land husbandry could provide hydrological benefits for both upstream and downstream users attracting payment possibilities for the environmental services. Valuation of the supply of environmental services, hydro-ecological linkages in watersheds and river basins and upstream and downstream benefits need further research for formulating mechanisms for payment for environmental services.

Acknowledgements

Authors acknowledge the facilities provided by International Centre for Integrated Mountain Development, Kathmandu, Nepal; G.B. Pant Institute of Himalayan Environment and

Development, Almora, India; and Kunming Institute of Botany, Kunming, China for completing this paper.

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