POLSKA AKADEMIA NAUK
INSTYTUT GEOGRAFII I PRZESTRZENNEGO ZAGOSPODAROWANIA
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RAINFALL, RUNOFF AND SOIL EROSION IN THE GLOBALLY EXTREME HUMID AREA, CHERRAPUNJI REGION, INDIA

Edited by Leszek Starkel and Surendra Singh

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GEOGRAPHICAL STUDIES

No. 191

OPAD, SPŁYW WODY I EROZJA GLEB W EKSTREMALNIE WILGOTNYM KLIMACIE W REJONIE CHERRAPUNJI, INDIE

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PREFACE

Exploitation, conservation and recovery of degraded natural resources are fundamental problems which environmental scientists are largely concerned with. It is a great challenge to provide answers to these questions in globally extreme rainfall conditions. The Meghalaya plateau represents one of the very few areas in the world having extremely high rainfall where deforestation and extensive land use practices have accelerated the process of water circulation leading to complete degradation of soils and vegetal cover. The problems of recovery of natural resources in these extreme conditions cannot be solved without detailed investigation of each link of the chain, starting from rainfall to runoff and then to soil erosion. This is the aim of this research undertaken by the Polish-Indian team.

This monograph is the product of close cooperation between Polish and Indian geographers who investigated the environmental parameters of landscape prevailing in Cherrapunji region. In 1996, the visit of Polish team (L. Starkel, W. Froehlich and R. Soja) from the Department of Geomorphology and Hydrology, Institute of Geography and Spatial Organization, Krakow, Polish Academy of Sciences (PAS) took place at the Department of Geography, North Eastern Hill University, Shillong, under the scientific exchange programme with Indian National Science Academy (INSA). Subsequently, in the summer of 1997 when the Indian team (S. Singh and H.J. Syiemlieh) visited Krakow, it was discussed and collectively decided to start a collaborative research work on geo-hydrological processes, related to the rainfall, runoff and soil erosion, acting in the extreme humid conditions of the Cherrapunji region. The proposed project was included, later on, in the Inter-Governmental Programme of co-operation between Department of Science and Technology (DST), Government of India, New Delhi and Polish Committee for Scientific Research (KBN), Government of Poland, Warsaw, which initiated a collaborative work during three consecutive years (2000–2002) with the following broad objectives:

– to examine the physical and hydrological properties of soils and regoliths;

– to find out the rainstorm characteristics and the conditions of water circulation;

– to evaluate and measure the intensity of rainfall, runoff and denudation rates in the Cherrapunjee region; and

– to find out about the causes of the existing geo-ecosystems degradation and possibilities of recovery of water resources, soils and vegetation cover.

This was the first phase of the investigation. Further investigations on eco-restoration (the recovery of soil and vegetation) of degraded landscape have been proposed for the second phase (2003–2005) of the research work to continue the existing cooperation.

Keeping these objectives in mind, an experimental design of the study was prepared and accordingly the investigations were carricd out. In fact, the rainfall-runoff relationship is a key link to understanding watershed behaviour in specific environmental conditions. Universal Soil Loss Equation (USLE) is applied by many scientists to estimate the soil erosion rate and to know the effects of various environmental factors. They used the 'Synthetic Approach' for the same purpose. But in the present work, an 'Analytical Approach' has been used and soil erosion rate is estimated by using radionuclides. More emphasis, however, is laid on the environmental aspects of landscape. Consequently, the proposed model was based the evolutionary geomorphic as well as present day process (hydrological) of landscape rather than on the use of USLE, which has limited applicability in extreme humid and senile conditions.

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We are grateful to the authorities of the North Eastern Hill University, Shillong and Polish Academy of Sciences, Warsaw for the approval and initiation of the cooperation between Polish and Indian scientists in investigating and looking into the problems of degraded landscape. This cooperation of scientists was formalized later at the inter-governmental level. We place on record our sincere thanks to the Department of Science and Technology (DST), New Delhi and State Commitee for Scientific Research (KBN), Warsaw that provided us with the inter-exchange scientific programme under which the regular visits of the Indo-Polish team were arranged. We also deeply acknowledge the approval of some additional visits of Polish partners under INSA–PAS exchange programme. Various state government departments, namely, the State Council of Science, Technology and Environment, Directorate of Agriculture, Forest Department, Shillong, were directly or indirectly involved in the present task. Our sincere thanks are due especially to Mr. R.D. West, Member Secretary, SCST&E, Dr A. Diengdoh, Director of Agriculture and the Secretary, North-Eastern Council (NEC), Shillong. We also express our thanks to the Circle Administration of Cherrapunji, non-governmental organizations like the Cherra Science Society and the Catholic Parish Church in Cherrapunji who took interest in our work and helped us at the local levels. We are deeply indebted to the Director and the staff members working in Regional Office of India Meteorological Department (IMD) Gauhati, and its Observatory at Cherrapunjee for supplying us with rainfall statistics. Our thanks and gratitude are due to the Regional Circle, Geological Survey of India, Shillong for organizing various field visits and providing geological literature, Mrs C. Swett, teacher at Ramakrishna Mission School, Cherrapunji, Mr. B. Patkowski from Polish Academy of Sciences, Krakow and several students of the Department of Geography, North Eastern Hill University, Shillong who helped in conducting field surveys throughout the project. Last but not the least, we are thankful to Prof. D.K. Nayak, Department of Geography, NEHU, Shillong, for taking the pains of going through the entire text of this report and editing the manuscript and also to Prof. P. Korcelli, Director of the Institute of Geography and Spatial Organization, PAS, Warsaw for providing the much needed support for the publication of this report.

Leszek Starkel
Surendra Singh

1. INTRODUCTION

Leszek Starkel, Surendra Singh

1.1. RESEARCH OBJECT AND AIM OF STUDY

Extreme rainfall creates specific conditions for landscape development in which the circulation of matter is accelerated after deforestation. The Cherrapunji region situated on the southern margins of Meghalaya plateau enjoys such extreme humid conditions at the global scale (Fig. 1). On account of accelerated geo-hydrological processes and increasing effects of anthropogenic forces, the natural resources (water, soil and biotic) of the area have been degraded to which special attention needs to be paid by the environmentalists and scientists of related disciplines.

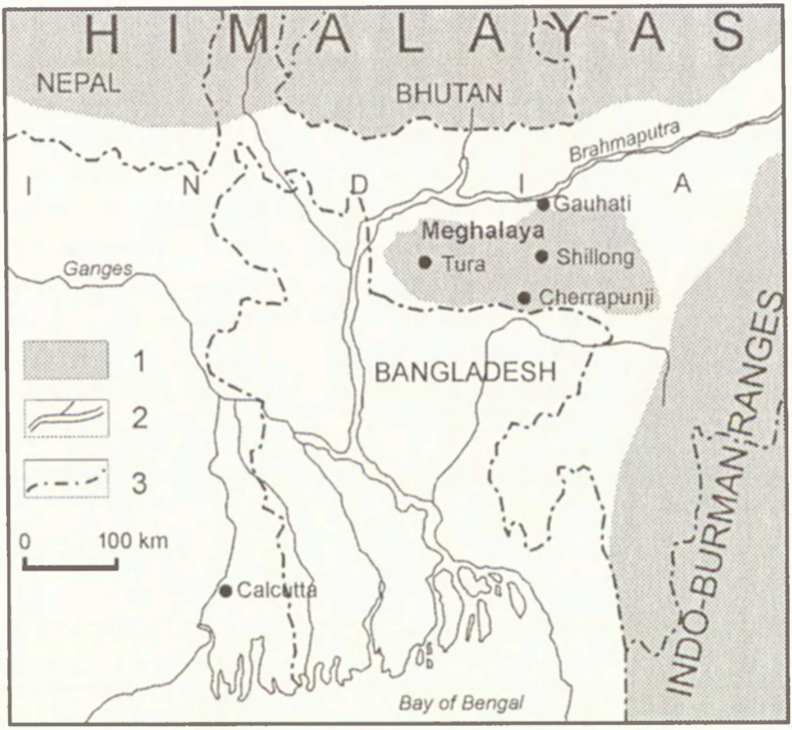


Fig. 1. Location of Meghalaya and Cherrapunji
1 – mountains and hills, 2 – rivers, 3 – international boundaries
Położenie Wyżyny Meghalaya i Cherrapunji
1 – góry i wyżyny, 2 – rzeki, 3 – granice międzynarodowe

Due to the unique geographic location of the Cherrapunji area in the North-Eastern part of India, it receives extremely high rainfall (of about 12,000 mm annually), which can be interpreted by comparing the locational characteristics of other such areas located elsewhere in the world. The geographic location of Cherrapunji near the Tropic of Cancer (at 25°15' N latitudes) would have otherwise made it a dry desert as experienced in other parts of the world situated on similar latitudes, notably the Great Indian desert of Rajasthan or the Sahara of Africa. In sharp contrast, the Cherrapunji area is exceedingly green largely due to the direct effect of south-west monsoon that supports tropical evergreen forest belt. The shifting of Inter Tropical Convergence Zone (ITCZ) over the continent and its (Meghalaya plateau) transverse location between the Eastern Himalayas on its north and the Bay of Bengal in the south leads to a direct contact of moisture laden winds with the plateau. Location of Cherrapunji on southern edge of the Meghalayan horst causes high rainfall to occur, while orographic effects control the processes of water circulation of this area (O'Hare 1997; Starkel, Basu 2000 p. 4). Monsoon circulation is checked by the southern foreland of the Meghalayan horst because of its steep slopes, vertical effects of rising moist air masses and conditions of condensation at about 1,000 m a.s.l. Similar amount of annual rainfall is also recorded in other areas of the world. For example, the Mt. Waialeale at an elevation of about 1,570 m a.s.l. situated in one of the main Hawaiian Islands, receives nearly 11,684 mm of average annual rainfall. Cherrapunji records may also be compared with conditions of Central Columbia (Central America) where nearly 13,300 mm of rain is received and the coastal Cameroon near the Gulf of Guinea where more than 10,000 mm rains have been recorded (Table 1). The equatorial zone of convectional circulation is connected with uniform rainfall pattern throughout the year and not concentrated during summers only as is the case in Cherrapunji area. Such seasonal variations in rainfall are extremely important as they create a complex nature of water circulation, weathering processes and landscape evolution.

Table 1. Extreme rainfall areas of the world

Name of the locality	Country	Elevation (m a.s.l.)	Average annual rainfall (mm)	No of years for observation
Quibdo	Columbia	36	8992	16
Cherrapunji	India	1313	11371	149
Mawsynram	India	1420	11872	38
Mt. Waialeale (Kauai)	Hawaii	1570	11684	30
Debundscha	Cameroon	10	10287	32

A second specific feature of Cherrapunji area pertains to its geological structure which controls the water circulation and evolution of relief. The horizontally bedded sandstones and limestones in the region overlie the metamorphic and igneous rocks, raised to an elevation of 1,200 to 1,900 m a.s.l. along the tectonic fault. They are dissected by deep gorges separating several spurs of the plateau. Cherrapunji is located at one of such spurs. Lithology of the area is reflected in a step-like morphology of slopes and river channels on the spur which differentiate the prevailing sandstone part and most of the southern limestone belt characterised by karst topography.

In such a rainfall regime and bedrock lithology, human activities play an exceptionally important role. For example, practice of shifting cultivation in the area has been an important cause of deforestation and soil erosion leading to degradation of natural resources, not only of vegetation (biomass) and soil but also of the water resources that tend to deplete due to the rapid overland flow. These processes of land degradation especially during the dry winter seasons are more or less identical to that of the semi-desert areas. It raises a question as to how the circulation of matter function in the geosystem under these circumstances? Is it possible to protect, restore or improve the natural resources at this stage of degradation? The recovery of soil, vegetation cover and a scientific management of water resources are issues that have to be tackled only with the help of a detailed investigation of hydrologie and geomorphic processes prevailing in this area.

1.2. STRUCTURE OF THE MONOGRAPH

The stated research problems, main objectives and the review of concerned literature have been arranged in the first two chapters of the present monograph. Chapter 3 includes the design of the study, materials collected, methods and techniques used for the present work. Following this, the characteristics of environment and land use of southern slope of the Meghalaya are elaborated in Chapter 4. The description of the Cherrapunji spur is included in Chapter 5. The details of the (experimental) Maw-ki Syiem catchment are described separately in Chapter 6 with a special emphasis on its response to rainfall received.

The studies of environmental processes are dealt with in a separate chapter (Chapter 7). It includes a detailed presentation of rainfall characteristics, presentation not only of the annual scale and seasonal distribution but also rainfall intensity during individual events. Chapter 8 describes the mechanism of water circulation, especially conditions of run-off and water storage. Next chapters discuss some aspects of rainfall-runoff relationship and water conductivity. The model of soil erosion (Chapter 11) is based on diversely scattered observations of present-day processes and strongly supported by the measurement of soil erosion at multi-annual scale based on analysis of radionuclides.

The last chapter contains the main findings and conclusions coupled with a model of water and matter circulation, tendency of transformation of natural systems with an attempt to prognosticate the long-term environmental change.

2. REVIEW OF LITERATURE

Surendra Singh

Cherrapunji has been in the eyes of the British not only for the purpose of investigation its environmental conditions but also for the judicial and administrative purposes. The British environmentalist, D.J. Hooker (1854) drew attention to problems of degradation in Cherrapunji. He described this area as barren, grassy land punctuated with occasional trees. In a report submitted to A.J.M. Mills in the year 1853, Fletcher mentions that the landscape in Cherrapunji is rocky in nature and is generally free from surrounding jungles. The temperature varies remarkably little throughout the year with a great quantity of rain of about 500" (i.e. 12,000 mm) annually precipitated in about 5 months time (Mills 1853). T. Oldham (1854) studied the geological structure and mineral resources of Cherrapunji plateau and from his experiences he made serious observations with regard to the environmental problems faced by this area.

A good number of geographers and geomorphologists have provided scientific explanation of the landscape evolution and formation of geomorphic features of this area. S.P. Chatterjee (1968) discussed in detail the characteristics of environmental and socio-economic problems of the Meghalaya Plateau. M.K. Bandyopadhay (1972) and S.K. Mazumdar (1976, 1978) provided a good description of relief features (structure controlled surface of plateau, deep canyons) and geomorphic processes of Meghalaya which contained details of Cherrapunji region too. L. Starkel (1972), during his first visit to India, studied the processes of soil erosion in various parts of India including the deforested Cherrapunji region.

During the last two and a half decades, since the inception of the North-Eastern Hill University at Shillong, many scholars including ecologists, geographers, agricultural scientists and foresters (Toky, Ramakrishnan 1981, 1982, 1983a, 1983b; Ramakrishnan, Ram 1988; Shankar et al. 1993; Khiewtam, Ramakrishnan 1993; Singh 1996) have published their researches on diverse problems of the area notably on poor soil fertility, disturbed ecological conditions, problems associated with agro-forestry, impact of shifting cultivation (jhum) on environment etc. A team of ecologists headed by P.S. Ramakrishnan worked on the effect of shifting cultivation on biomass of surface soil before and after fire. It was found that pH stabilised while organic carbon and nitrogen contents decreased in the soils of various grasslands in Cherrapunji (Ram, Ramakrishnan 1988). Effects of runoff and percolation on the soils of the grassland communities were also observed and the study concluded that the grasses of Cherrapunji area were getting more annual inputs of nutrients through rainfall than its losses. In such conditions of degraded ecosystems, an integrated view of its ecorestoration was considered important by the team led by R.S. Tripathi, an eminent ecologist from the North-Eastern Hill University. The suggested strategy for ecorestoration was to conserve the gene-pool, biodiversity, grass cover and forests of Cherrapunji area (Borthakur 1995; Tripathi et al. 1995).

A few studies on hydrological processes operating in much disturbed ecological conditions were conducted by research station of Indian Council of Agricultural Research (ICAR) located at Barapani, on the northern slope of the Meghalaya plateau. Through establishment of experimental plots and micro-watersheds, the runoff on various hill slopes was predicted by using the parameters of unit hydrograph (Sathapathy 1994/95, 1995/96). The water harvesting techniques for the North-Eastern Hill areas were also suggested by adopting water balance approach (Sathapathy 1996). A calculation on the direct runoff in the catchment located east of Cherrapunji was done by P. Prokop (1999) using remote sensing data to understand geomorphological parameters and employing Geographical Information System (GIS) technique and Soil Conservation Service (SCS) method for assessment of runoff.

Only a few studies are available which describe geological controls in the formation of scarps and flat valley floors over the plateau, karstification, in armouring of slopes by creeping blocks and development of drainage systems with steep valley heads in the Cherrapunji region (Rai 1991; Starkel 1989, 1996). The problems of lithological control of relief features and tectonic activities are also important ingredients of some of the studies concerning geological literature (Evans 1964; Chatterjee 1968; Mazumdar 1986; Das 1992).

It is a pity that hydro-meteorological conditions prevailing in Meghalaya plateau has not been studied extensively in spite of available monthly as well as annual weather records for long series of time (nearly 100 years) in the office of Indian Meteorological Department, Pune. Only a few preliminary attempts have been made by geographers, agricultural scientists and government agencies to interpret the atmospheric conditions, circulation of water and the orographic effects on rainfall distribution and, upto same extent, the water budget in connection with the interpretation of land use, agronomic and climatic factors of the area (Starkel 1972; Gopalakrishnan 1995; Singh 1996). Rainstorm characteristics were presented on the basis of 20 years monthly as well as hourly records of significant rainstorms occurring in different seasons in the Cherrapunji area (Singh, Syiemlieh 2001). Meteorological statistics have been used by ccologists, soil scientists, geographers, anthropologists only as a background material of their work to justify the causes of land use variations, forest ecology, degraded ecosystem, etc. (Ram, Ramakrishnan 1988; Tripathi et. al. 1995). In none of these works, scientific explanations of the hydro-meteorological phenomena, which are relevant for the study of the characteristics of 'monsoon bursting', soil moisture and available water resource, are forwarded to further the understanding of the nature of hydrographs and surface runoff. Nevertheless, in many records and reports on rainfall and hydrological regime, the extreme rainfall in Cherrapunji is cited as the heaviest recorded intensities in the global scale (Philemon 1995; Singh 1996).

From this review, it may be safely concluded at least in the case of Cherrapunji region, that there appears to be a deficiency of literature on scientific explanation of hydrological processes and nature of soil erosion in this area of heaviest rainfall at the global scale. Studies on rainfall-runoff-soil erosion relationship seem to be of great importance in understanding of the mechanism of environmental changes in this extremely humid climate.

3. MATERIALS, METHODS AND TECHNIQUES

Leszek Starkel, Surendra Singh, Wojciech Froehlich, Paweł Prokop, Roman Soja

Information and data for the study on rainfall, water circulation and soil erosion for Cherrapunji region are collected either: a) from different published and written sources or b) by mapping and conducting different kinds of field survey, concentrated on characteristics of soils and water properties and evaluation of soil erosion by contents of radionuclides and c) the monitoring of rainfall, runoff, water discharge and chemical denudation.

3.1. MATERIALS COLLECTED AND THEIR SOURCES

Explanation of environmental degradation needs quantitative data to justify the results. There are many and varied sources of generation of data specially through maps and published records.

a) Maps

Interpretation of relief, river network and land use component of the southern slope of Meghalaya is based on the analysis of R.F. 1:50,000 scale topographic maps and on satellite images (remotely sensed data). Some information is also collected from available various cartographic and written documents on geology, soils, and land use changes (Table 2).

Table 2. Secondary sources of research material

No	Name of statistics	Years	Source
1.	Information on elevation, drainage and settlement pattern etc.	1966–1967	Toposheet 1:50 000, No 78O/11, 78O/14, 78O/15, Survey of India, Dehra Dun
2.	Land use/land cover	1998	Satellite images IRS-1D, National Remote Sensing Agency, Hyderabad
3.	Information about geology and lithology	1974, 1987	Regional Circle, Geological Survey of India, Shillong
4.	Rainfall and temperature statistics, rainfall pluviograms	1901–2000	India Meteorological Department, Pune; Regional Meteorological Office Gauhati; Public Work Department, Mawsynram
5.	Soil information	1993	Toposheet 1:250 000, 78O, Regional Office, National Bureau of Soil Survey, Landuse Planning, Jorhat
6.	Forest cover statistics	1998	Forest Department Govt. of Meghalaya, Shillong
7.	Population	1991	Census of India, New Delhi
8.	Agriculture and crop statistics	1997–98	Directoriate of Agriculture, Govt. of Meghalaya, Shillong

The use of toposheets No 78O/11 and 78O/15 prepared by Survey of India, Dehradun which cover most of the parts of Cherrapunji spur and its surroundings, is useful to trace out the natural boundaries of spur and canyons. The 20 m contour interval of topographic map determines clearly such terrain features which have been taken as a base to delineate the boundary of the spur.

Geological maps are much generalised for the Meghalaya State and the detailed ones present small fragment of it. In order to get the picture of Cherrapunji spur, there is a need to compile different maps, sketches and profiles.

b) Satellite images

Interpretation of spatial distribution of land use/land cover systems of the area of southern slopes of Meghalaya plateau was done through IRS-1D data acquired on 8 November 1998 (post-monsoon season). The 3 spectral bands (1, 2, 3) were geo-referenced using control points from the 1:50,000 topographic maps of the area which include sheets numbers 78O/11, 78O/14 and 78O/15. The maximum likelihood algorithm was applied for image classification. A Normalized Difference Vegetation Index (NDVI) was generated from the near-infrared and infrared bands for estimating the vegetation density.

c) The rainfall records

Meteorological station at Cherrapunji at an elevation of about 1,313 m a.s.l. (Fig. 2) began to register the rainfall records in the year 1852 (Oldham 1854). During the first phase (before 1902), the recording was done simultaneously at two stations, namely the Meteorological Observatory (Cherrapunji) and the Police Station, located only at 1 km distance from each other. The series of records are not seen similar with frequent breaks of data. For the elaboration of rainfall trends, monthly records for a period of 90 years (1902–1992) were received from Indian Meteorological Department (IMD), Pune. Daily records for the years 1986–2000 and pluviograms for two years 1999 and 2000 were collected from the Meteorological Department, Regional Office, Gauhati.

Mawsynram, another area of extreme rain, is located about 16 km west of Cherrapunji at elevation of about 1,420 m a.s.l. (Fig. 2). There is only a rain gauge station under the Public Works Department, Government of Meghalaya from where daily records have been collected for the last part of the century, that is, from 1982 to 2001.

There is no availability of rainfall statistics at hourly time scale. The meteorological Observatory of IMD is equipped with syphoned pluviograph, which may distinguish total rainfall during period longer than 15–20 minutes. The records are unpublished. In the Indian meteorological data publications, the rainfall intensity is calculated at a scale of 24-hours. The monthly rainfall

Fig. 2. Location of measurement points and experimental catchment Maw-ki Syiem
1 – flat or hilly deforested plateau, 2 – forested areas, mainly steep slopes of canyons, 3 – experimental catchment, 4 – location of pluviometers, (P – parish church, Ch – Cherrapunji meteorological observatory, T – Thangkarang Park), and meteorological stations (M – Mawsynram), 5 – location of water pH and conductivity measurements (N – Nongpriang, L – Laitkynsew), 6 – elevations in meters

Położenie punktów pomiarowych i zlewni eksperymentalnej Maw-ki Syiem
1 – płaska lub pagórkowata wylesiona wyżyna, 2 – obszary porośnięte lasem, głównie strome stoki i kaniony, 3 – zlewnia eksperymentalna, 4 – położenie pluwiometrów (P – kościół, Ch – obserwatorium meteorologiczne w Cherrapunji, T – Park Thangkarang) i stacji meteorologicznych (M – Mawsynram), 5 – położenie punktów pomiaru pH i przewodnictwa wody (N – Nongpriang, L – Laitkynsew), 6 – wysokości w metrach

intensity is calculated only from total amount of rainfall dividing it by number of rainy days (Singh, Syiemlieh 2001).

d) The statistical records

Records on land-use and human activities have been collected for the present research. Such data were available with different governmental as well as non-governmental organisations (Table 2). Land-use and agricultural statistics were also collected from the Directorate of Agriculture. Data related to the settlement and population were taken from District Census Hand Book, Census of India.

3.2. FIELD SURVEY AND LABORATORY MEASUREMENTS

Field surveys were conducted and the related laboratory techniques were used at different levels of work. They include: a) geomorphologic mapping and survey of landforms, b) studies on grain size composition and hydrological properties of soils, and c) use of radionuclide technique to assess the rate of soil erosion and sedimentation.

a) The field surveys

Mapping of relief types was prepared for the middle part of Cherrapunji spur at a scale of R.F. 1:25,000 partly based on field survey. In order to generate detail data and monitor the hydrological and geomorphic processes, a small experimental catchment at Maw-ki Syiem with an area of about 22 ha was selected. This catchment is situated on the uniform geological structure (horizontally bedded sandstones and siltstones) with typical undulating relief of the plateau and is only 1.0 km westward from the Meteorological Observatory, Cherrapunji at similar elevation (1,315–1,390 m a.s.l.). At the first stage of survey, a topographical map of the catchment was prepared at a scale of R.F. 1:2,000. The elevations, distances and angles are measured by using compass, altimeter and clinometer; it is found that the catchment covers an area of about 219,138 m^2. It is to be noted here that this area of catchment varies insignificantly from the areal extent which is measured from toposheets at a scale of R.F. 1:25,000 (i.e. 219,589 m^2). For the accuracy and practical purpose, an average value of both the size calculations has been taken into account, which is 22 ha.

Topographic maps became a background for detailed geomorphic survey as well for longitudinal profiles of main creeks and slopes. The cross-sections of Maw-ki Syiem creek at a scale of R.F. 1:2,000 indicating the lithological control and changes in longitudinal profile were also made.

b) The grain size composition and hydrological properties of soils

The role of surface cover and available soil types are major sources of runoff generation and the sediment source. Physical properties of soils of the area were examined by analyzing grain size composition, infiltration rate and water holding capacity. The grain size composition was analysed in order to measure the concentration of ^{210}Pb, ^{226}Ra, ^{241}Am and ^{137}Cs by collecting samples from waste surface covers, shallow soils and floodplain overbank deposits. The measurements of grain size composition of skeletal fraction were performed by wet sieve method and by the use of laser analyser Mastersizer S of Malvern Instruments Ltd. for 0.05–3500 μm particles. In order to collect the samples and measurement of water storage of soils, the 200 cm^3 capacity Kopecky's cylinders were ment of water storage of soils, the 200 cm^3 capacity Kopecky's cylinders were used. The above measurements were made in the Homerka Laboratory of Fluvial Processes, Institute of Geography and Spatial Organisation, PAS.

The measurements of infiltration rate during the dry season (in November 2000) were made by the flooding method using Burger's cylinder of 1,000 cm^3 volume (100 mm depth of rainfall, i.e. 100 dm m^{-2}) at down slope and in valley bottom profiles of the Maw-ki Syiem experimental catchment. These measurements of infiltration rate were done on the ground surface and at the depths of 5, 10, and 30 cm up to 5 times. The infiltration rate of every 10 mm was registered. Usually extreme rainfall events occur on the saturated ground surface. For simulation of these conditions, the experiments were performed with infiltration of 200 mm rain depth on the slope as well as valley bottom of the experimental catchment. The Burger's cylinder was filled successfully by water of a quantity of 1,000 cm^3 (i.e. to 100 mm of rain).

c) The use of ^{210}Pb, ^{226}Ra, ^{241}Am and ^{137}Cs to evaluate the rate of soil erosion and sedimentation

Maw-ki Syiem experimental catchment and surrounding areas were surveyed for the assessment of soil loss and deposition of overbank deposits estimated by applying the ^{210}Pb, ^{226}Ra, ^{241}Am and ^{137}Cs methods and using two soil erosion and sedimentation models. Caesium-137 is widely used as a technique for estimating net soil loss within drainage basins (Loughran 1989; Ritchie, McHenry 1990; Walling, Quine 1990). Caesium is a fallout radioisotope of atmospheric nuclear weapon tests and nuclear power plant accidents. The 137Cs is absorbed to surface soils and has been used as a tracer of soil down slope movement. This tracer technique as used for soil samples of different sites (uneroded, eroded as well as deposited) for the assessment of soil erosion in experimental catchment, the net erosion and deposition in different valley sectors have been expressed by comparing the eroded reference site samples results with uneroded ones.

In order to analyse the soil erosion rate through ^{137}Cs technique in the experimental catchment, the five spots as soil reference sites were chosen on the top of grass-hillcrests. The soil samples to the depth of the bedrock for each reference site are collected to understand the differentiation in the soil results. Soil cores were obtained by hammering a 75 mm diameter steel corer. Two transects of slopes were taken at regular 10 m intervals of slope, from which samples are collected up to 35 cm depth. Further to the downstream part of experimental catchment, the overbank deposits and footslope waste surface cover were sampled at three spots to the depth of bedrock or coarse gravel disaggregated and passed through a 2 mm sieve. The <2 mm fraction being packed into Marinelli beakers for gamma-ray spectrometry using an Ortec HPGe coaxial detector at the Homerka Laboratory of Fluvial Processes, Institute of Geography and Spatial Organization, PAS. The activity of ^{137}Cs at the 661.62 keV photopeak was calibrated using International Atomic Energy Agency standard Soil-327.

3.3. MONITORING OF THE PRESENT-DAY PROCESSES

Monitoring includes mainly the continuous measurements of rainfall duration and intensity as well as seasonal observations of water level, river discharge and chemical denudation.

a) Rainfall monitoring

In order to understand the mechanism of rapid runoff and soil erosion, it is important to get information on rainfall intensity at a scale of one minute unit of time. For this purpose, the oscillation pluviometers well-equipped with data logger (SEBA Hydrometrie, Germany) were installed in the study area recording data with each oscillation of 0.1 mm.

SEBA pluviometer has input surface of 200 cm^2 and is installed just on the ground surface close to the siphon type pluviometer in Indian Meteorological Observatory, Cherrapunjee. The SEBA pluviometer is reinforced by long life dry battery cells working upto 6–8 months. Memory card of 512 KB is used to make the registration of rainfall up to 15,000 mm possible in one stretch. The records were collected twice a year using laptop for down-loading the rainfall data.

Measurement of rainfall at several localities should help to understand the spatial pattern of high precipitation. The first pluviometer was installed on the flat roof of the Catholic Parish in Cherrapunji about 1,430 m a.s.l. in May, 1999 and later it was shifted to the IMD Observatory Cherrapunji at elevation of about 1,320 m a.s.l. in November, 2000. In order to find out the orographic effect on rainfall variation, another pluviometer was installed on the edge of plateau at Thangkarang Park at an elevation of about 850 m a.s.l. It was installed in the month of July 2000.

The records collected were compared with the daily data registered at Meteorological Observatory at Cherrapunji. There was a 5 to 7% fluctuation in the daily records registered by the SEBA pluviometers and the Observatory rain gauge. The pluviometer recorded 7% lesser rain. However the rainstorm characteristics and rainfall pattern are analysed by using pluviometric records.

It appears that some short-time breaks in rainfall registration occured (especially at Thangkarang Park) because the inlet of the pluviometer was blocked by insects.

The collected records available in the form of text file were elaborated through conversion software by changing the text file into monthly table of hourly rainfall compiled by Z. Bury. With his help, it was possible to illustrate the daily course of rainfall in the form of traditional pluviogram used in most of automatic recorders.

b) The runoff measurements

Direct measurements of river discharge of the Maw-ki Syiem creek were made 3 times: a) on 20 November, 1999, b) 12 November, 2000, and c) 24 November, 2001. Discharge rates were measured respectively at 10, 11 and 5 sites (cross-section) of main creek and tributaries by means of volumetric methods, and the measurements were repeated three times to generate mean discharge data.

It was done because the installation of permanent limnigraph at the mouth of catchment was not possible on account of financial constrains and lack of man power under the project. However on the road bridge at the mouth of catchment, a simple water-level gauging station was prepared in November, 2000 by W. Froehlich. The measurements were taken by Mrs. C. Swett during rainy days from January 2002 onwards. During the period of 11 months (from January to November, 2002), a total of 59 measurements were made to compile the results.

c) Water conductivity and chemical denudation

Measurements of hydrogen ion concentration (pH) and conductivity of rainy and flowing water were carried out utilizing of Polish instruments made by Elmetron Co. Measurements of pH were done by pH-ionometer CI-315 equipped in glass electrode and automatic temperature compensator. Water conductivity was measured by the use of microcomputer conductivity meter CC-315 with platinum sensor C-317 (constant 0.519) and automatic temperature compensation. The margin of error may reach a level of 5% at maximum in the band of 0–199 microsimens.

Measurements of pH and water conductivity of rainy water were made at an interval of 1–2 hours, depending on the rainfall intensity. The samples from rain water were collected in the polystyrene cup of 35 cm in diameter. A large sample of rainfall that was about 150 cm^3 was taken for measurement. The samples of flowing streams were also collected by filling sampling bottles directly from the field or outside at an hourly interval. The water samples of deep Um Stew canyon near Cherrapunjee were collectcd for a detail analysis of chemical denudation in Cherrapunjee area.

Water sample measurements were generally made several times in the months of June-July in the year 2000, 2001 and 2002, and flowing creeks in winter 1998. More detailed survey of surface waters in Maw-ki Syiem catchment was done in May 1999. While a general sample single measurements of surface water werc made for the southern slopes of Meghalaya Plateau to compare the results.

4. ENVIRONMENT AND LAND USE OF THE SOUTHERN SLOPE OF MEGHALAYA

4.1. GEOLOGY

Paweł Prokop

The Meghalaya plateau standing as an assymetric horst situated between the Himalayan foredeep and Bengal Plain rises in its central part up to 1,960 m a.s.l. Its southern scarp is much steeper than the northern slope characterised by rather gentler slope. It is built up by the basement of Achaean gneissic complex and quartzites of Shillong Group (Oldham 1854; Medlicott 1869; Mazumdar 1986). Discordant, Upper Proterozoic granites and minor greenstone plutons intrude the basement and form large South Khasi and Mylliem batholiths (Goswami 1960; Ghosh et al. 1991). Both formations are deeply jointed and weathered, depending on varied resistance. On the southern margins, this basement is broken by basaltic rocks of Sylhet trap of the Jurassic age. Southern slopes in the central longitudinal transect of Meghalaya are covered by the sedimentary rocks of the late Cretaceous-Palaeogene transgression, several hundreds meters thick. From the base, it starts with basal conglomerates and glauconitic sandstones of Mahadek formation belonging to Khasi Group (Table 3, Fig. 3). The Jaintia Group then forms another stratum with sandstones and clays of Langpar Formation of the Palaeocene age. Its upper part follows a complex of Mid-Eocene Shella Formation, composed of 5 members; namely, Lakadong limestone, Lakadong sandstones and shales, Umlatdoh limestone, Narpuh sandstone and Prang limestone. Entire sedimentary sequence is crowned by shales and sandstones of Kopili Formation and at present it can only be seen in the downthrown block. In the S–N transect of southern slopes of Meghalaya, a characteristic facial transition from littoral marine to coastal-deltaic facies may be encountered which are manifested in the temporal transgressions and regressions. All these sedimentary units are more or less horizontally bedded or inclined 2° to 5° towards south.

Meghalaya Plateau has been strongly modified due to prolonged tectonic activities and peneplanation. The post Precambrian land-masses experienced peneplanation resulting to a flat levelled surface preserved till today. S.P. Chatterjee (1968) recognised a number of erosion surfaces at varying altitude with the highest one 1,860–1,920 m a.s.l. compared with „Gondwana

Table 3. Stratigraphy of the central-southern Meghalaya Plateau (based on GSI 1974; Mazumdar 1986; Das 1992)

Age	Group	Formation	Thickness (m)	Member	Lithology
Eocene	Jaintia	Kopili	500		Splintery shales with minor sandstone
		Shella (Sylhet limestone)	600	Prang limestone Narpuh sandstone Umlatdoh limestone Lakadong sandstone Lakadong limestone	Alternation of limestone and minor sandstone
		Therria (Cherra)	100		Ferruginous sandstone in the main plateau with limestone around Therria
Palaeocene		Langpar			Calcareous buff coloured sandstone and clay
Cretaceous	Khasi	Mahadek (Mahadco)	150		Glauconitic (Arkose) sandstone and gritty sandstone
		Bottom conglomerate	25		Conglomerate, arkose
		Jadukata (Gumaghat)	140		Sandstone-conglomerate alternations
Jurassic	Sylhet Trap		600		Basalt, alkali basalt, rhyolite, acid tuff
Proterozoic		Granite	intrusive		Porphyritic and coarse granites, quartz, biotite and microline
		Khasi greenstone	intrusive		Dolerites, epidiorite, amphibolite
		Shillong Group			Quartzite and phyllite conglomerate
Archaean		Gneissic Complex			Gneiss, schist, biotite, pyroxene

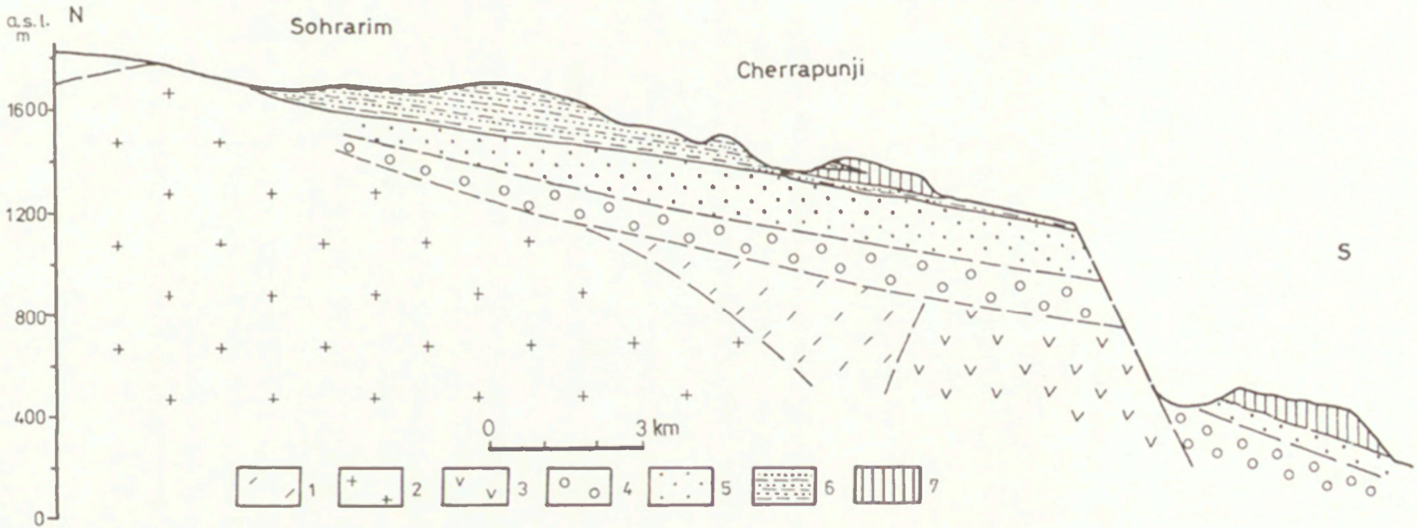


Fig. 3. Geological transect of southern slope of Meghalaya (compiled by L. Starkel)
1 – Gneissic Complex, 2 – Shillong Group, 3 – Granite, 4 – Sylhet Trap, 5 – Mahadek Formation, 6 – Langpar Formation, 7 – Therria (Cherra) Formation

Przekrój geologiczny przez południowy skłon Meghalaya (oprac. L. Starkel)
1 – Kompleks gnejsów, 2 – Grupa Shillongu, 3 – granity, 4 – trap Sylhetu, 5 – formacja Mahadek, 6 – formacja Langpar, 7 – formacja Therria (Cherra)

surface". By the end of Jurassic, the southern margin of Khasi hills experienced eruption of basalts. The Sylhet trap is comprised mainly of basalts, marking the first major tectonic event. In the southern fringes of the plateau, a complex tectonic line commonly known as the Dawki fault was formed. This fault runs in E-W direction and forms the contact between the Shillong Plateau and the Sylhet trough. It is a 5-km wide fault zone characterised by extensive fracturing (Evans 1964) and steep dips of Pliocene and Pleistocene strata (Khan 1978). The Meghalaya Plateau had relatively stable shelf conditions when formations of Jaintia Group of rocks were deposited. The major uplift of the plateau to 1000 m order occurred in Neogene time (Photo 1). However, Pliocene rocks are not represented on the Plateau (Chakraborty 1972; Das 1992). The complicated tectonic scarp was dissected by the deep canyons. The sediments derived from them form extensive alluvial fans in the Bengal depression.

4.2. THE RELIEF

Leszek Starkel

Central part of the Meghalaya plateau of about 1,800–1,960 m a.s.l. elevation has a mature, structure-controlled landscape with relief energy 50–150 m (Photo 2). Its residual ridges which are formed by quartzite beds separated by flattenings and shallow valleys exhibit a character of Appalachian relief (Chatterjee 1968). The relief which is dissected by the wide valley floors with meandering rivers is the product of long planation and weathering (Bandyopadhay 1972). The type and depth of regolith of lateritic origin depend on bedrock lithology and on the slopes of Mylliem granite reaches to 20 m depth with core stones. Contrary to it, the southern spurs of the plateau are built up of sedimentary rocks and are developed in the forms of table land. It is generally inclined to the south composed of several flattenings separated by cuesta-like scarps and drained by network of creeks, gradually incised deeper and deeper.

Margins of the plateau form very steep slopes with 2 or 3 storey scarps which have 800–1000 m high straight or dismembered by amphitheatres of valley heads with waterfalls at every 1–2 km. This escarpment is interrupted by a system of deep canyons cut into the basement of igneous or metamorphic rocks. The upper part of their sides is steep, often vertical, and is bordered by complexes of resistant limestones and sandstones (Photo 1).

Photo 1. Large canyon of Um Stew to the east of Cherrapunji spur (L. Starkel)
Kanion rzeki Um Stew po wschodniej stronie Płaskowyżu Cherrapunji (L. Starkel)

Photo 2. Maw-ki Syiem catchment, upper Cherrapunji (ca. 1400 m a.s.l.) and higher northern part of the spur (1500–1700 m a.s.l.) (P. Prokop)
Zlewnia Maw-ki Syiem, górne Cherrapunji (ok. 1400 m n.p.m.) i wyższa północna część płaskowyżu (1500–1700 m n.p.m.) (P. Prokop)

Photo 3. Clouds rising near the margin of flat Cherrapunji Spur. Photo made in the middle of rainy season (R. Soja)

Chmury wznoszące się na krawędzi Płaskowyżu Cherrapunji. Zdjęcie wykonane w środku pory deszczowej (R. Soja)

Photo 4. Evergreen floor of deep canyon near Cherrapunji (P. Prokop)
Wiecznie zielone dna głębokiego kanionu kolo Cherrapunji (P. Prokop)

4.3. THE SOILS

Pawel Prokop

The southern slope of Meghalaya is not homogenous with respect to parent material, relief and climate. Thus, the regional variations in physical and chemical characteristics of soil are so distinct. They fall under three orders: Ultisols, Alfisols and Inceptisols (according to *Soil Survey Staff* 1975). The soils are excessively drained, acidic in nature (pH varies from 4 to 6) with organic carbon from 1 to 3% (*Regional Office of...* 1993).

The upper parts of the southern slope are occupied by metamorphic and igneous rocks: gneisses, schists and granites. They are covered by old weathered deposits being stable for a long time and have given rise to very deep soils up to 2 m. At some places quartz layers are found which have shallow soils. The soil texture varies from sandy loam to clay loam. Due to continuous leaching, the soils are depleted of their inherent fertility (poor in calcium, phosphorus, nitrogen, potassium and iron oxide) in most parts (Shankar et al. 1993). The soils have poor performances of base saturation (much lesser than 35%) and fall under Ultisols. The soils of quartzite areas have higher base saturation and fall under Alfisols and Inceptisols (*Agriculture and Soil* ...1987). All these soils, if proper irrigation is provided can produce a large variety of crops. However the hilltops usually have very low soil thickness largely due to the effects of erosion.

The young sedimentary complex has comparatively less weathered soil material. Soils are generally shallow to moderately deep in nature with dominant depth ranging from 25 to 50 cm. The soils are mixed with a lot of gravels and the presence of large boulders on the surface indicates the scale of soil erosion (Pandey et al. 1993). They are also leached to varying degrees though the extent of leaching is less conspicuous than in other parts of plateau. Excessive erosion has given rise to sharp peaks and deep gorges. Most of the soils fall usually under the kind of Alfisols and Inceptisols. If the soil depth is more than 1.3 m, it falls generally in to the order of Ultisols (*Agriculture and Soil* ...1987).

Varying degrees of erosion have affected the soils of the entire area. Relief differences and steep rainfall gradient with a significant range of temperature regime has complicated the process of soil formation in this area. These natural conditions are further influenced by human activities, especially the agricultural practices found in the upper part of southern slope coupled with mining of coal and limestone over the sedimentary complex deposits in the marginal areas (Tripathi, Pandey 1991).

4.4. THE CLIMATE

Roman Soja

Meghalaya plateau is located in an area influenced by monsoonal climate. Mean annual temperature fluctuates from 15°C in the uppermost parts to 25°C at the southern foot of the plateau. Amplitudes of mean monthly temperature difference reach about 10°C.

In the most elevated parts of the plateau, temperatures fall below 0°C in winters though snowfall is rare. However, even in areas adjacent to Cherrapunjee, elevated up to 1,300 m a.s.l. in the valley floors, needle ice had been observed due to inversion of temperature (Starkel 1972). The rainfall has a typical seasonal distribution and about 80% of precipitation is recorded from May to September. However, characteristic feature of rainfall here is its acute areal variation with typical asymmetry. The Bengal Plains which are located at lower elevations of about 100 m a.s.l. receive less than 2500 mm rain annually, while Cherrapunji and Mawsynram areas nearer the edge of the plateau (Photo 3) get an average annual precipitation ranging from 8,000 to 24,000 mm. A station at Mawphlang located about 25 km inside from the edge and situated at 1,800 m a.s.l. gets only 3,300 mm average annual rain (Fig. 4). Farther to the north, at the highest ridge of the plateau close to Shillong from where

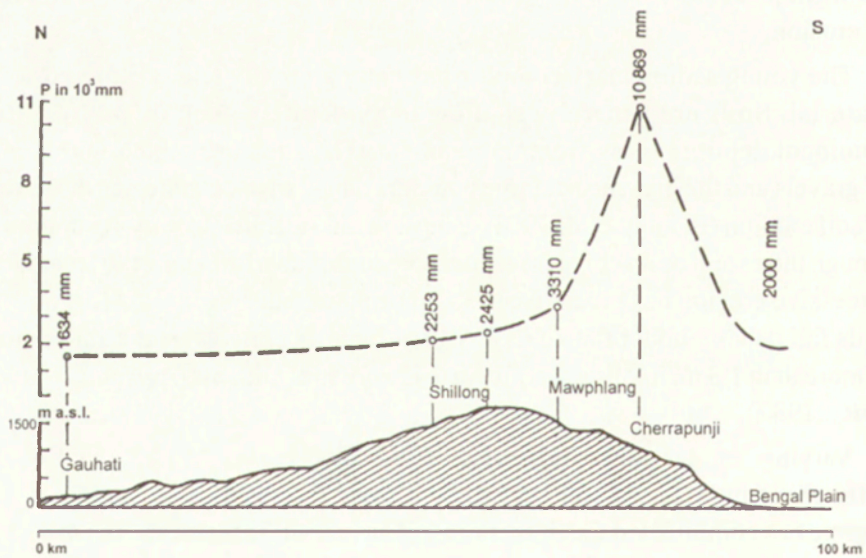


Fig. 4. Cross section of Meghalaya Plateau with annual precipitation curve (L. Starkel et al. 2002)

Przekrój przez Wyżynę Meghalaya z krzywą średnich rocznych opadów (L. Starkel i in. 2002) the northern slope starts, the average annual rainfall is recorded at 2,500 mm. At the northern foothills of the plateau, close to Guwahati, the rainfall recorded is much less i.e. only 1,634 mm annually.

4.5. VEGETATION AND LAND USE

Paweł Prokop

Forests constitute major land cover in Meghalaya (*Forest Survey of India* ... 1991, Fig. 5). Tropical evergreen and subtropical evergreen are two climax forest types. The others types exclude Sal (*Shorea robusta*) plantations are secondary formations (Ramakrishnan, Kushwaha 2001). The present day pine and bamboo forests, shrubs and grasslands represent degraded vegetation which has been developing under biotic and edaphic stresses. The secondary forest formation is the result of large-scale timber extraction during the colonial and few decades of post-colonial phases (Singh, Singh 1992). In more recent times, even bamboo forests have been degraded due to large supplies made to paper and pulp industry (*Agriculture and Soil* ... 1987). Besides timber extraction, deforestation and secondary forests formation are the consequences of shifting cultivation as a small-scale perturbation in 2–3 ha plots cleared by the farmers (Ramakrishnan 1992).

Champion and Seth (1968), based on field data and own observations, grouped forest vegetation of Meghalaya into two broad types: 1) the tropical moist deciduous forests that occur on the lower foothills, 2) the subtropical broad-leaved forests that can be seen on hills above 1,100 m a.s.l. where rainfall is generally in excess of 2,000 mm annually. Haridasan and Rao (1985) grouped forests on the basis of their altitudinal location, rainfall and species composition. They distinguished three types of forests in Meghalaya: tropical, subtropical and temperate forests with the following sub-types on the southern slope of Meghalaya (Table 4):

1) Tropical semi-evergreen forests that occupy areas at lower elevation up to about 200 m a.s.l. (Fig. 6). The main features of such forests are the leafless canopy during the dry season. It also includes at places evergreen and tropical moist deciduous species and show distinct stratification. The upper canopy is composed of *Bischofia javanica*, *Dillenia indica*, *Dillenia pentagyna*, *Ealeocarpus floribunda*, *Mesua ferrea*; the middle storey contains *Ficus racemosa*, *Mangifera sylvatica*, *Dalbergia assamica*; the lower layer is made up of *Antidesma bunius*, *Alchornea tiliaefolia*, *Premna barabata*. Lianas and epiphytes like orchids also grow in such forests.

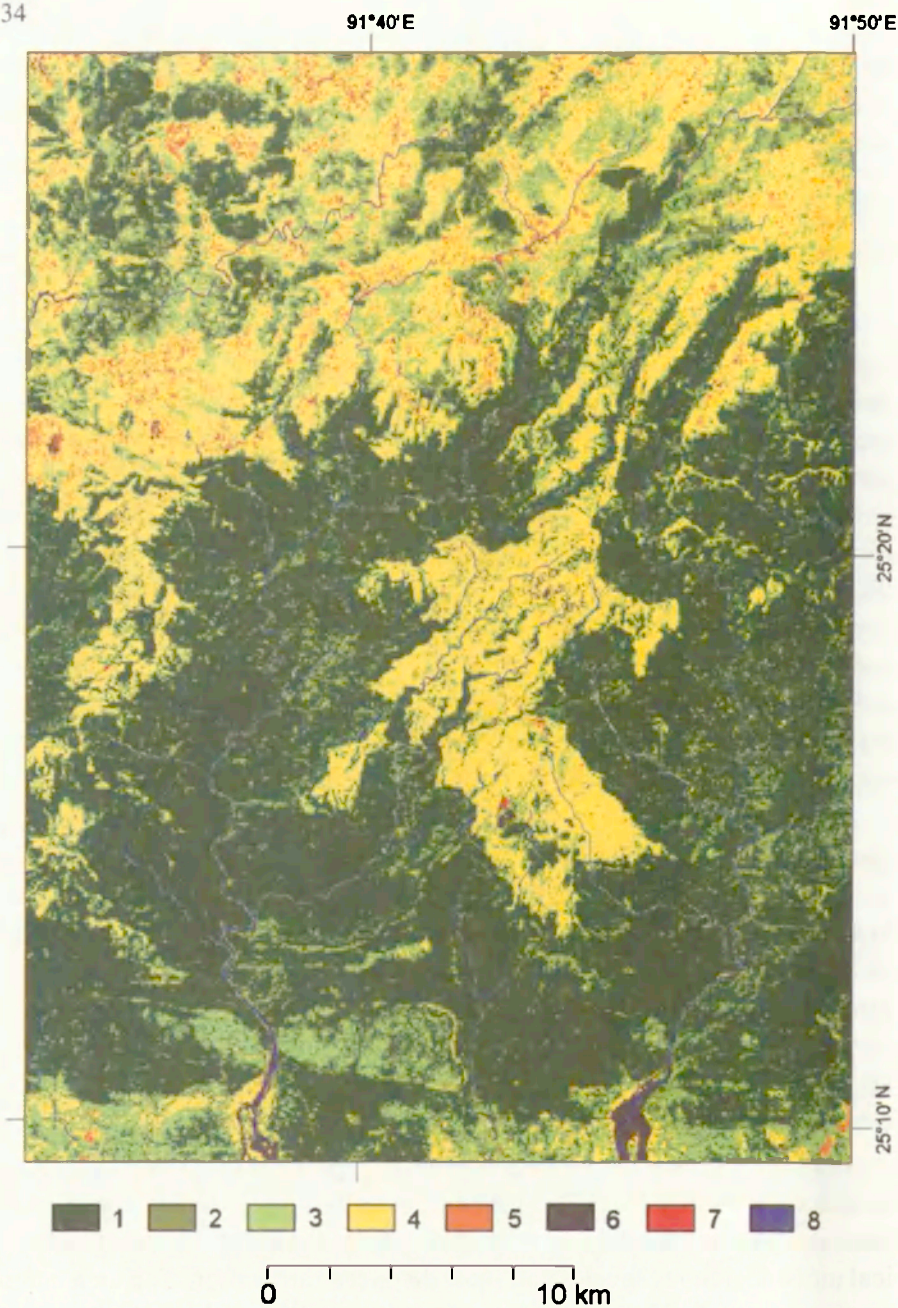


Fig. 5. Land cover/land use map of Cherrapunji spur and surrounding areas(compiled by P. Prokop on the basis of satellite image IRS-1D)
1 – subtropical deciduous forest, 2 – subtropical pine forest, 3 – scrub, 4 –grassland, 5 – cropland, 6 – rock outcrop, 7 – built up area, 8 – water

Mapa pokrycia i użytkowania terenu Cherrapunji i okolic (oprac. P. Prokop na podstawie zdjęcia satelitarnego IRS-1D)
1 – subtropikalne lasy liściaste, 2 – subtropikalne lasy sosnowe, 3 – zarośla, 4 – trawy, 5 – uprawy, 6 – wychodnie skalne, 7 – zabudowania, 8 – wody

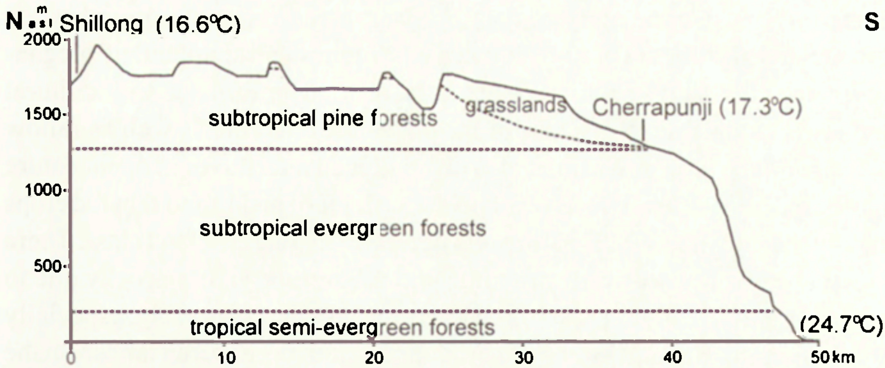


Fig. 6. Transect of vegetation vertical belts on southern slope of Meghalaya Plateau (by P. Prokop). Annual average temperature in parentheses

Przekrój przez piętra roślinne południowego skłonu Wyżyny Meghalaya (oprac. P. Prokop). W nawiasach średnie roczne temperatury

2) Subtropical evergreen forests occur approximately up to 1,300 m elevations and in deep georges along the river banks (Photo 4). The upper canopy is occupied mainly by *Castanopsis spp.*, *Manglietia insignis*, *Lithocarpus elegans*, *Vitex spp.* The lower layer is constituted by *Adina cordifolia*, *Daphne involucrata*, *Milletia prainii*. The shrub layer comprises mostly of *Antistrophe oxyantha*, *Blumea balsamifera*, *Lyonia ovalifolia*, *Rauvolfia serpentina*. Forests are of medium height rarely exceed 20 m. The flora of this forest is remarkable but it is locally affected by shifting cultivation (jhum) especially in the lower parts of the plateau. These areas are often covered by secondary formation with bamboo species like *Dendrocalamus hamiltonii*, *Dendrocalamus gigantea* and *Bambusa bambos*. Some exotic species like *Eupatorium odoratum*, *Mikania micrantha* and *Galingosa parviflora* have invaded the secondary forests, abandoned jhum fallows, cultivated fields and wastelands (Kushwaha et al. 1981, 1983)

Upper parts of the southern slope are occupied by subtropical pine forests. It is considerably influenced by annual fires. These forests are dominated by *Pinus kesiya* (or *Pinus insularis*) with some broad-leaved species like *Acacia delbata*, *Quercus griffithi*, *Schima sp*.

3) Temperate forests (broad-leaved hill forests) which assume covered grassland areas in the past are found only in small pockets along southern slopes above 1,300 m a.s.l., where rainfall is highly intensive and winter is relatively severe. At lower elevations, these forests are intermixing with tropical and subtropical elements.

The land use/land cover classes of the southern slopes of Meghalaya plateau are distinguished under different categories such as deciduous forest, coniferous forest, grassland, cropland, built-up areas, rock outcrop and water. Climate and altitudes (1,600–1,900 m a.s.l.) of the central upland of Meghalaya plateau favour the occurrence of grasslands and pine forests. Agricultural land is also available in this part of the plateau. Cultivable as well as fallow lands are mixed with grass situated on the flattened interfluves in open mature valleys and hill-slopes. This is why only large fields of paddy and rain fed crops (mainly potatoes and cabbages) are registered as separate cropland class. There is lesser grass cover towards the south and the surface is often rocky due to increasing surface mining of coal and limestone. Extensive grazing, especially on the Cherrapunjee and Mawsynram spurs, has left more barren lands. On the other side, the deep canyons are covered with deciduous forests punctuated by small patches of grasses where the fallow fields of shifting cultivation may be seen on the steep slopes. Arecanut, orange, banana, jackfruit and pine-apple plantations may be seen in the lowest parts of valleys. These plantations are not delineated on the map as separate class due to small size of the patches and mixed with deciduous forests.

5. ENVIRONMENTAL CHARACTERISTICS OF CHERRAPUNJI SPUR

5.1. RELIEF AND GEOLOGY

Paweł Prokop, Leszek Starkel

Cherrapunji spur has a shape of tennis rocket with a narrow handle in its upper northern part, which is less than 1 km wide. Its ondulated surface varies from 1,800 m in the north to 1,100 m a.s.l. in the south at the distance of 20 km. In its middle and lower portions, it has a width of up to 5–10 km (Fig. 7). The spur is surrounded by the system of canyons of about 600–1,000 m deep (Fig. 8). These canyons belong to the Umiew river system which is on its western side while the deep valley of Um Sohra river is located on the east (Photo 1). The valley sides are very steep. Their upper parts are built of highly resistant sandstones and shales. Many small creeks may be seen with magnificent waterfalls (Photo 5). Their edges are considered as retreating which is shaped by rock falls and slumps (Starkel 1996). Over the spur surface, the main valley network is represented by parallel creeks of NNE–SSW direction at about 1–2 km distance, which are up to 8–10 km long and gradually incised along flat valley floors. Especially, the flats are the fragments of the spur with wind gap valley sections which have been isolated by captures of their headwaters by tributary canyons.

Cherrapunji spur in its northern and middle part is built up of almost horizontally and parallel beds. The Therria ferruginous sandstones are overlain by less resistant Lakadong sandstones and siltstones with three thin horizons of coal (Figs. 3 and 10). Both series represent the coastal-deltaic facies. More resistant sequences of beds form several irregular scarps on the surface (especially distinct on the northern sides above 1,500 m and on the southern edges below 1,400 m a.s.l). The resistant beds are expressed in the steeper portions of valley sides and in waterfalls and rapids on the consequent stream flows. The horizontal bedding facilitates the formation of flat structure controlled interfluves as well as the lateral expansion of the rocky river channels (Photo 6) which are disproportionately wide to the length of the river and catchment's size (Fig. 11). More gentle forms are developed over the less resistant complexes of beds and in interfluve areas which can be visualised in the topography of undulated flattened hills similar to herd of lambs (Fig. 8). The gradual

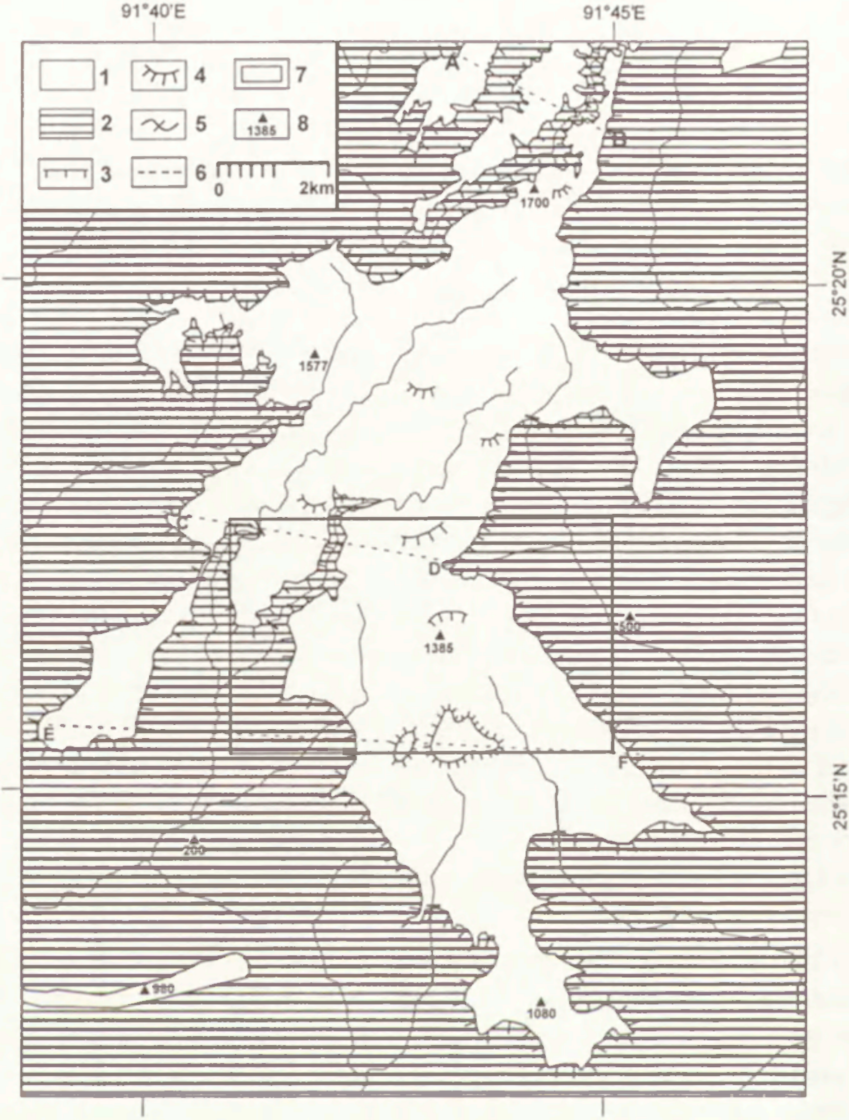


Fig. 7. Morphology of Cherrapunji spur (by L. Starkel)
1 – flat or hilly deforested plateau, 2 – steep slopes of canyons, 3 – scarps of canyons, 4 – escarpments, 5 – stream with waterfalls, 6 – cross sections, 7 – location of geomorphic map of central-southern part of Cherrapunji spur (Fig. 11), 8 – elevations in meters

Rzeźba Płaskowyżu Cherrapunji (oprac. L. Starkel)
1 – płaski lub pagórkowaty wylesiony płaskowyż, 2 – strome zbocza kanionów, 3 – krawędzie kanionów, 4 – progi denudacyjne, 5 – rzeki z wodospadami, 6 – linie przekrojów, 7 – położenie mapy geomorfologicznej środkowo-południowej części Płaskowyżu Cherrapunji (Fig. 11), 8 – wysokości w metrach

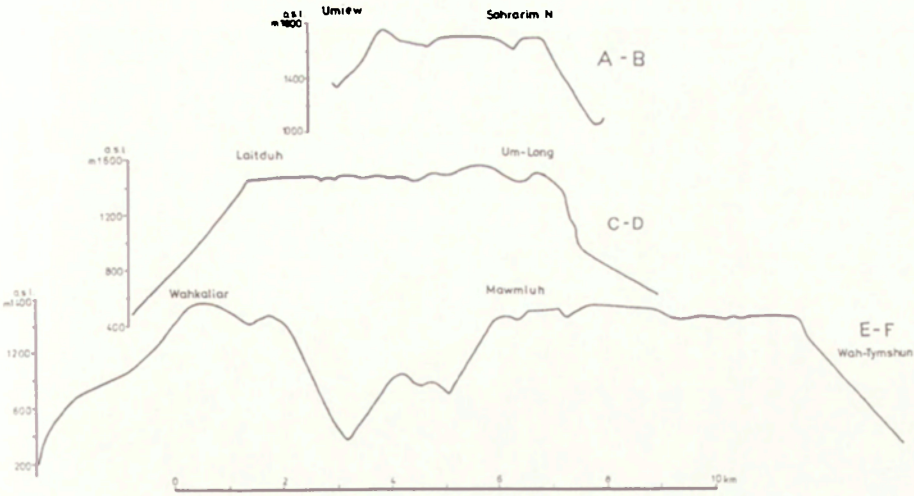


Fig. 8. Crossections of the Cherrapunji spur (indicated on Figure 7) (by L. Starkel)
Przekroje poprzeczne przez Płaskowyż Cherrapunji (wskazane na rycinie 7) (oprac. L. Starkel)

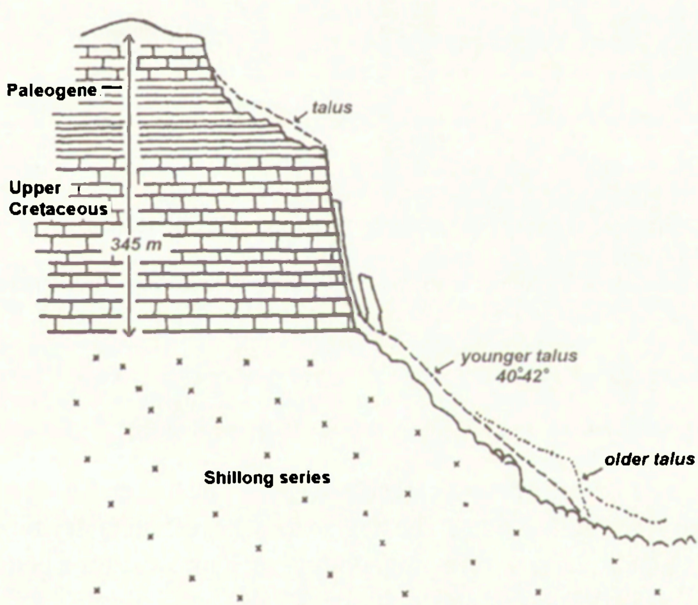


Fig. 9. Profile of vertical cliff with waterfalls (simplified, based on Mawsmai Falls) (L. Starkel 1996)
Profil pionowej ściany z wodospadami (uproszczony, oparty na wodospadach w Mawsmai) (L. Starkel 1996)

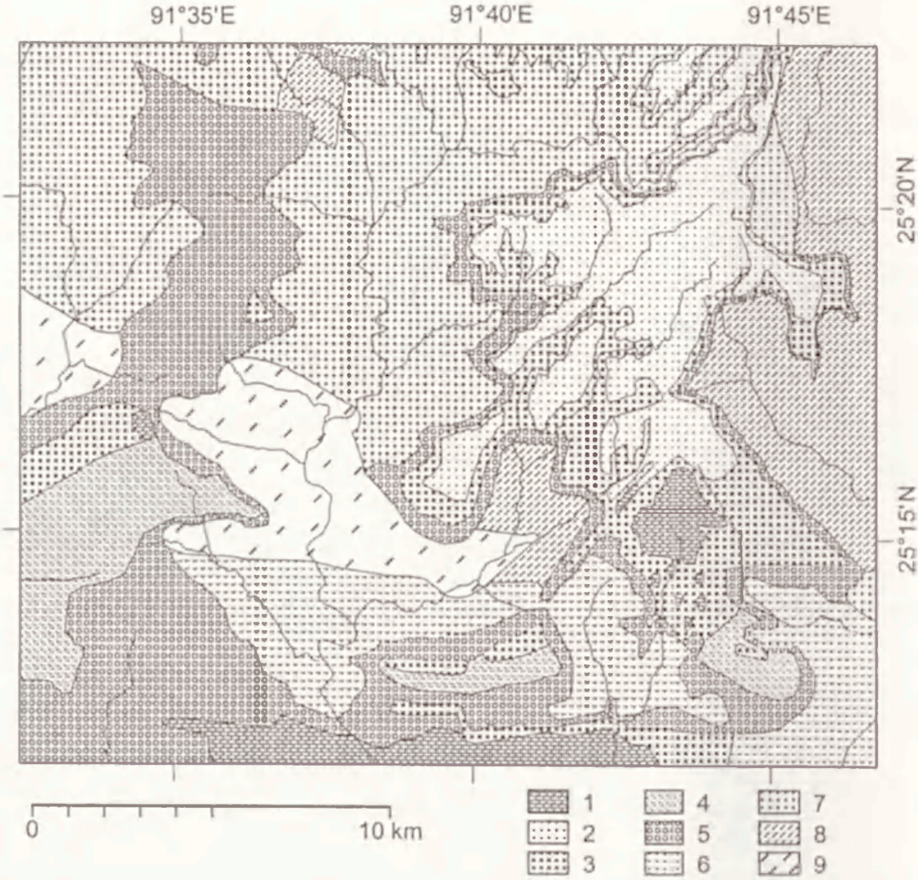


Fig. 10. Geological sketch of Cherrapunji spur (compiled by P. Prokop on the basis of various sources)
1 – Shella limestone, 2 – Shella sandstone, 3 – Therria formation, 4 – Langpar formation, 5 – Mahadek formation, 6 – Sylhet Trap, 7 – Granites, 8 – Shillong Group, 9 – Gneissic Complex

Szkic geologiczny okolic Cherrapunji (oprac. P. Prokop na podstawie różnych źródeł)
1 – wapienie Shella, 2 – piaskowce Shella, 3 – formacja Therria, 4 – formacja Langpar, 5 – formacja Mahadek, 6 – trap Sylhetu, 7 – granity, 8 – grupa Shillongu, 9 – kompleks gnejsów

downcutting to the next (lower) resistant sandstone bed causes the lowering of base level for valley sides. The degradation of residual lateritic crust and sliding of blocks derived from upper more resistant sandstone beds are specially visible in deforested areas (Starkel 1996).

The southern and lowest portion of Cherrapunji spur is built up mainly of limestone complexes of littoral facies. Therefore, the valley floors in these parts are characterised by rising limestone mesas of 100 to 150 m hight with steep scarps and typical karstic topography like small uvala and poljes or system of

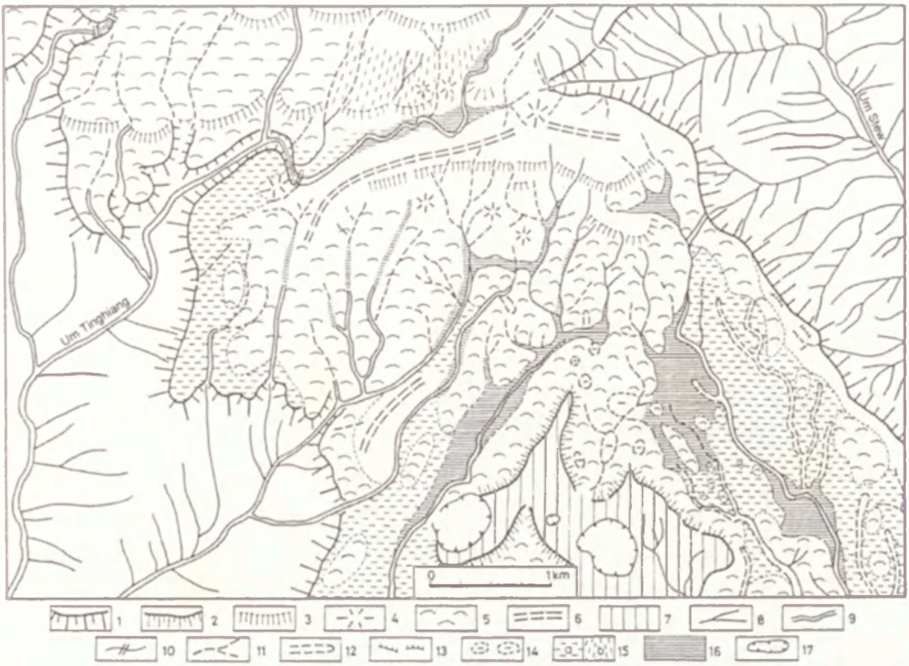


Fig. 11. Geomorphological sketch of central-southern part of Cherrapunji spur (surveyed by L. Starkel)
1 – steep scarps of canyons, 2 – escarpments of limestone mesas, 3 – other structure controlled scarps, 4 – residual hills, 5 – hilly landscape, 6 – broad flat ridge, 7 – limestone mesa, 8 – incised channels or gullies, 9 – wide incised channels, 10 – waterfalls, 11 – flat-bottom small valleys, 12 – other shallow valleys, 13 – scarps of rockfalls or slumps, 14 – karstic depression, 15 – higher valley bottom or glacis, 16 – valley floors (mainly structure controlled), 17 – limestone quarries

Mapa geomorfologiczna środkowo-południowej części Płaskowyżu Cherrapunji (kartowanie L. Starkel)
1 – strome krawędzie kanionów, 2 – progi wapiennych stoliw, 3 – inne strukturalne progi, 4 – ostańcowe wzgórza, 5 – rzeźba pagórkowata, 6 – szeroki, płaski grzbiet, 7 – wapienne stoliwo, 8 – wcięte koryta i wciosy, 9 – szerokie wcięte koryta, 10 – wodospady, 11 – małe płaskodenne doliny, 12 – inne płytkie doliny, 13 – krawędzie obrywów i zerw, 14 – krasowe obniżenia, 15 – wyższe dna dolin lub glacis, 16 – dna dolin (głównie uwarunkowane strukturą), 17 – kamieniołomy wapieni

caves (Fig. 11). Several small creeks (including the Maw-ki Syiem draining experimental basin) disappear in ponors. This water reappears in the karst springs and at the steep escarpment of the Cherrapunji spur over the Sylhet basalt.

5.2. THE SOILS

Pawel Prokop

The parent material of surface (sandstone and limestone sedimentary deposits) which is exposed to high rainfall plays major role in the soil formation over Cherrapunji spur. The horizontally bedded rocks have shallow soils compared to upper parts of Meghalaya which, on the granitic and metamorphic rocks, have originally 10–20 m thick regoliths. The anthropogenic factors like deforestation, former agricultural fields, overgrazing and extensive mineral exploitation are responsible for accelerated soil erosion processes and, resulting in the removal of the topsoil. The spatial variations in soils are due to variations in local relief and prevailing land cover/land use systems.

According to the soil studies done by the *Agriculture and Soil Division* (1987) and *Regional Office* (1993), the soils of Cherrapunji area belong to two orders: Alfisols and Inceptisols which may be classified under Ultic Hapludalfs and Typic Dystrochrepts subgroups respectively. The soils are coarse in texture, very shallow to moderately deep in its thickness but dominant soil depth ranges from 25 to 50 cm. If the soil depth is more than 1.3 m, it falls rarely in the order of Ultisols.

The grassland soils are directly exposed to heavy rainfall and are extremely shallow (0–30 cm), with gravelly pavement of about 2–5 cm and, somewhere large boulders on the surface may be seen (Tripathi, Pandey 1991; Shankar et al. 1993). Contrary to this, the forest soils under thick vegetation including the soils of adjoining canyons (except very steep slopes >30°) are thicker (up to 130 cm), more fertile and rich in humus. The forest soils of Cherrapunji spur are usually light grey, lateritic, acidic and rich in organic matter. The thick detrital layer is associated with fine roots of trees and ground vegetation (Khiewtam, Ramakrishnan 1993).

The soils are acidic in nature and this may be attributed to the leaching of cations like calcium, magnesium and potassium from the soil profile owing to high rainfall. The soil nitrogen content has been recorded to be about 0.94%

Table 5. Properties of soils of two contrasting land cover types around Cherrapunji

Land cover	Stone>5 mm (%)	Gravel 5-2 mm (%)	Sand (%)	Silt (%)	Clay (%)	pH	Soil moisture 1/3 bar tension (%w/w)	Texture	OC(%)	Bulk density
grass	53.3	22.3	80.6	11.0	8.4	4.5	17.0	s, ls	2.8	1.3
forest (protected and reserved)	14.5	4.0	75.0	18.9	6.1	4.2	23.4	ls, sl	3.6	1.1

NB: The averages are based on the analysis of 10 samples. s – sand, ls – loamy sand, sl – sandy loam in undisturbed cover and is much lower (about 0.15%) at degraded sites around Cherrapunji (Pandey et al. 1993). A comparative account of physical properties of soils supports that there are significant variations in the texture of soils in two contrasting vegetation cover: a) the grassland and b) the subtropical broadleaved forests (Table 5).

5.3. LAND COVER AND LAND USE

Hiambok J. Syiemlieh, Pawel Prokop

The prevalence of noticeable extent of grassland areas and subtropical forests is the main characteristic feature of the landscape of Cherrapunji spur and its adjoining areas (Fig. 12). Grass cover makes up the major part of landuse around Cherrapunji. Degraded lands of the spur are covered mainly by *Arundinella* type of grasses, namely, *Osbeckia spp.*, *Carex spp.*, *Fimbristilis spp.* and *Arisaema echinatum Roxb.*, which grow in different proportions at different sites. These grasses grow slow due to soil nutrient depletion caused by impermeable substratum, heavy precipitation, combined with seasonal burning and extensive grazing (Pandey et al. 1993).

The broad forest classes are subdivided by using NDVI index as forwarded by the Forest Survey of India in its classification. They are, dense forest (tree canopy density of 40% and more), open forest (tree canopy density ranging from 10% to 40%) and scrub area (tree lands with less than 10% crown density).

The natural forests are by and large confined only to the steep slopes of deep gorges and in small patches in the protected or sacred grove areas. The forests in deep gorges around and over Cherrapunji spur belong to two broad types, a) temperate forests and b) subtropical evergreen forests respectively (Haridasan, Rao 1985). Champion and Seth (1968) have classified temperate forests as 8B/C2, the Khasi subtropical wet hill forest.

The largest patches of the sacred groves and protected forest are located in the southern parts of the Cherrapunji spur around Cherrapunji town and Mawsmai village where isolated patches cumulatively account for a few hundred hectares. These forest patches are not under fire, grazing or felling influence and have dense vegetation with high species diversity. The average height of trees does not usually exceed 10–15 m. The major tree species found in these forests are *Castanopsis kurzii*, *Ficus nemoralis*, *Myrica esculenta*, *Manglietia insignis*, *Schima wallichi*, *Quercus spp.*, *Ligustrum nepalense*. The shrub and herb patches are well developed along the streams and open spaces. The herb patches generally comprise of *Commelinaceae* and *Araceae* (Rao et al. 1990).

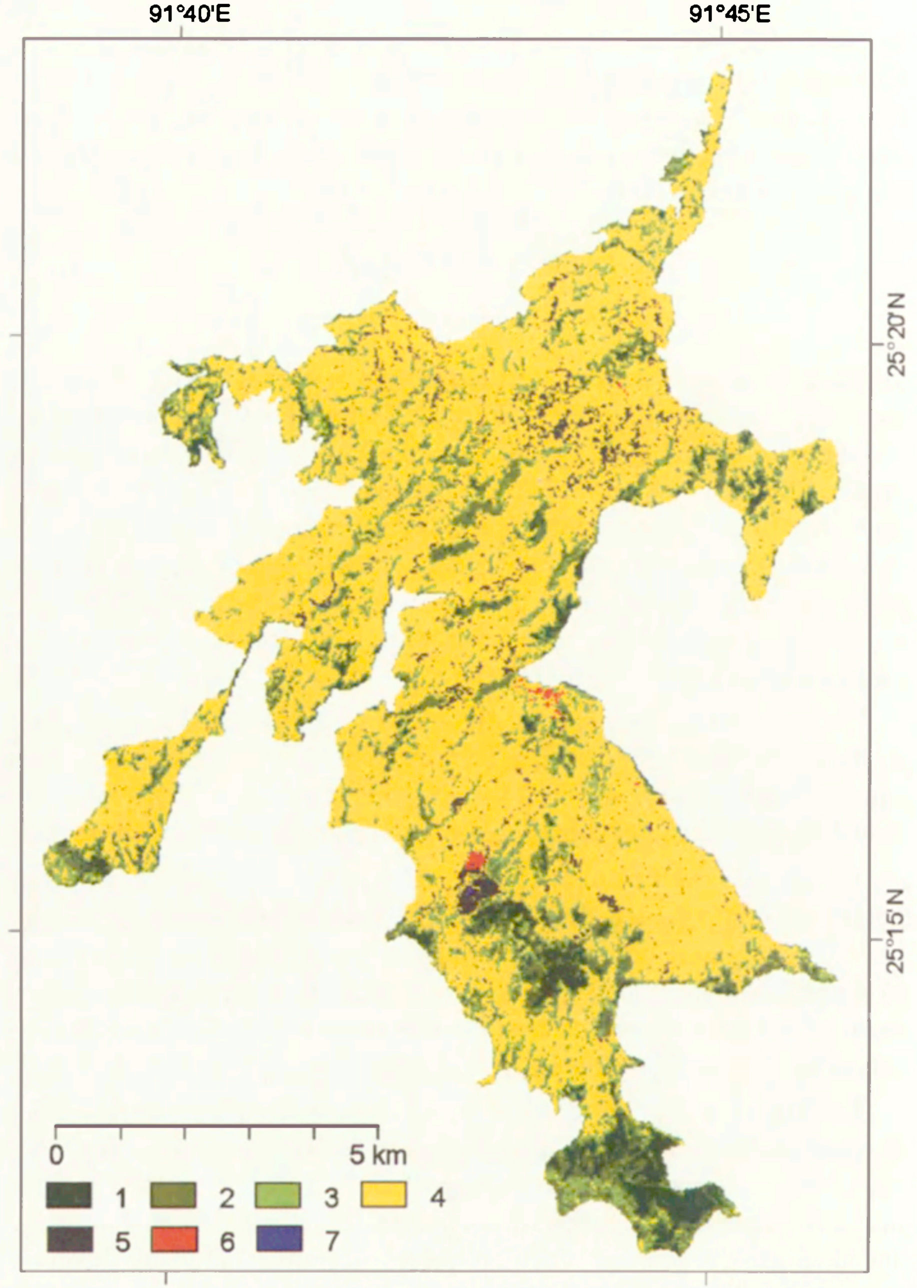


Fig. 12. Land cover/land use of Cherrapunji spur (compiled by P. Prokop on the basis of satellite image IRS-1D)
1 – subtropical dense deciduous forest, 2 – subtropical open deciduous forest, 3 – scrub, 4 – grassland, 5 – rock outcrop, 6 – built up area, 7 – water

Pokrycie i użytkowanie terenu Płaskowyżu Cherrapunji (oprac. P. Prokop na podstawie zdjęcia satelitarnego IRS-1D)
1 – gęsty subtropikalny las liściasty, 2 – rzadki subtropikalny las liściasty, 3 – zarośla, 4 – trawy, 5 – wychodnie skalne, 6 – zabudowania, 7– wody

Photo 5. Hanging valley rejuvenated with steep scarps and waterfalls west of Cherrapunji in Umiew catchment (P. Prokop)

Wisząca dolina niżej odmłodzona ze stromymi progami i wodospadami na zachód od Cherrapunji w zlewni Umiew (P. Prokop)

Photo 6. Unrejuvenated upper valley section with flat floor controlled by bedrock in western part of Cherrapunji Spur (L. Starkel)

Nieodmłodzony górny brzeg doliny z płaską skalną podłogą w zachodniej części płaskowyżu Cherrapunji (L. Starkel)

Photo 7. Exploitation of coal beds along the road upslope of Cherrapunji (P. Prokop)
Eksploatacja ławic węgla opodal drogi powyżej Cherrapunji (P. Prokop)

Photo 8. Exploitation and burning of limestone at the margin of limestone mesa south of Cherrapunji (L. Starkel)
Eksploatacja i wypalanie wapieni na krawędzi stoliwa wapiennego na południe od Cherrapunji (L. Starkel)

Table 6. Land cover/land use on the Cherrapunji spur (total area 71.4 km^2)

Land cover/land use class	Area (%)
Grassland (degraded land)	68.1
Subtropical dense deciduous forest	4.7
Subtropical open deciduous forest	13.8
Scrub	10.0
Builtup areas	0.2
Rock outcrops	3.1
Water	0.1

The unprotected forests, bamboo formation and dense shrubs are strongly affected by grazing and exploitation for domestic uses.

The clearance of forest is also observed around Cherrapunji area where surface limestone and coal mining activities are taking place (Fig. 12, Table 6, Photo 7, 8). The three larger built up areas on the Cherrapunji spur which are affected by industrial and quarrying activities are visible on the satellite image. They are Cherrapunji – the headquaters of Shella-Bholaganj Block as urban agglomeration, Mawmluh – the largest industrial area centre of the Cement Factory and Laitryngew village where coal mining activities are extensively practiced.

5.4. THE SETTLEMENT

Surendra Singh

Distribution of settlement in Cherrapunji area is seen along the edge of spur starting from village Sohrarim (1,694 m a.s.l.) located on the north-eastern part of the spur to Cherrapunji settlement (1,312 m a.s.l.) on its eastern edge through a series of settlements; Laitryngew village is situated on a coal mine. They are connected by road running parallel to the bluffs of Um Stew River in its east. Likewise, many small settlements are located on the northern edge of the spur and are connected with unmetalled road and footpaths (Mawkma and Laitlyndop). The settlement Mawkma and its hamlets were developed near old coal mines close to them on the small ridge which is acting as a water-divide in the area. There are also traces of abandoned villages and hamlets which were connected with the old coal mines.

The dissected foreland of the spur has the large settlements on its western edge. Laitduh is in the forefront of south-centre while Wahkaliar and Mawsahew are on the south-western forefront. These are the major settlement foci. The villages located in the vicinity of spur-edges all around may have opportunity to use two types of geo-ecosystems: a) the upper barren part of the spur where coal mining and limestone quarries are prevalent and b) the steep slopes with different forest which are available for jhum cultivation, lumbering and horticulture activities.

The settlements are mainly longitudinal in shape either along the small streams or the roadsides. Rectangular shape of settlements is controlled by the micro-relief features. On the whole, settlements follow dispersed type except Cherrapunji town which has its two centres: the upper (old one) on the hill with the market and lower one located 100 m below on the plain with administrative centre. Being historically known and as an administrative headquarters, Cherrapunji has largest concentration of population in the area.

Cherrapunji's (locally called Sohra in Khasi) population was recorded 7,777 persons according to Census of India 1991 in which bulk of the work force is employed in the manufacturing and house hold industries and in construction work. The town is famous for collection and marketing of oranges, betel-nuts and a variety of herbs.

6. GEOMORPHIC FEATURES AND ENVIRONMENT OF EXPERIMENTAL CATCHMENT – MAW-KI SYIEM CREEK

6.1. LOCATION AND GEOLOGY

Leszek Starkel

The Maw-ki Syiem catchment of about 22 ha is located in the central-southern part of the Cherrapunji spur on the slope of the latitudinal ridge of about 1,420 m a.s.l. The upper part of this catchment starts at an elevation of about 1,390 m and goes down to 1,314 m a.s.l. and ends near the bridge on the road connecting cement factory from Cherrapunji town (Fig. 13, Photo 2). The

Fig. 13. Hipsometric map of Maw-ki Syiem catchment (contours every 5 meters) (surveyed by L. Starkel and W. Froehlich). 1 – perennial creeks, 2 – seasonal or episodic creeks, 3 – forest and scrub, 4 – main road

Mapa hipsometryczna zlewni Maw-ki Syiem (poziomice co 5 m) (oprac. terenowe L. Starkel i W. Froehlich). 1 – cieki stałe, 2 – cieki okresowe lub epizodyczne, 3 – lasy i zarośla, 4 – główna droga

Meteorological Observatory is located at about 1,313 m a.s.l. one kilometer eastward from it.

The downstream of catchment extends over a flat depression after crossing the bridge towards the south. The flat depression ends further south at a distance of about 250 m where the stream disappears in a karstic ponor. The experimental catchment is about 800 m long and 320–360 m wide. It has relatively uniform substratum and is built up mainly of ferruginous sandstone beds, interbedded with siltstones of various resistance of Therria formation and in the topmost part of Lakadong sandstone with lowest thin coal lenses. The bedrock is tightly jointed and deeply weathered.

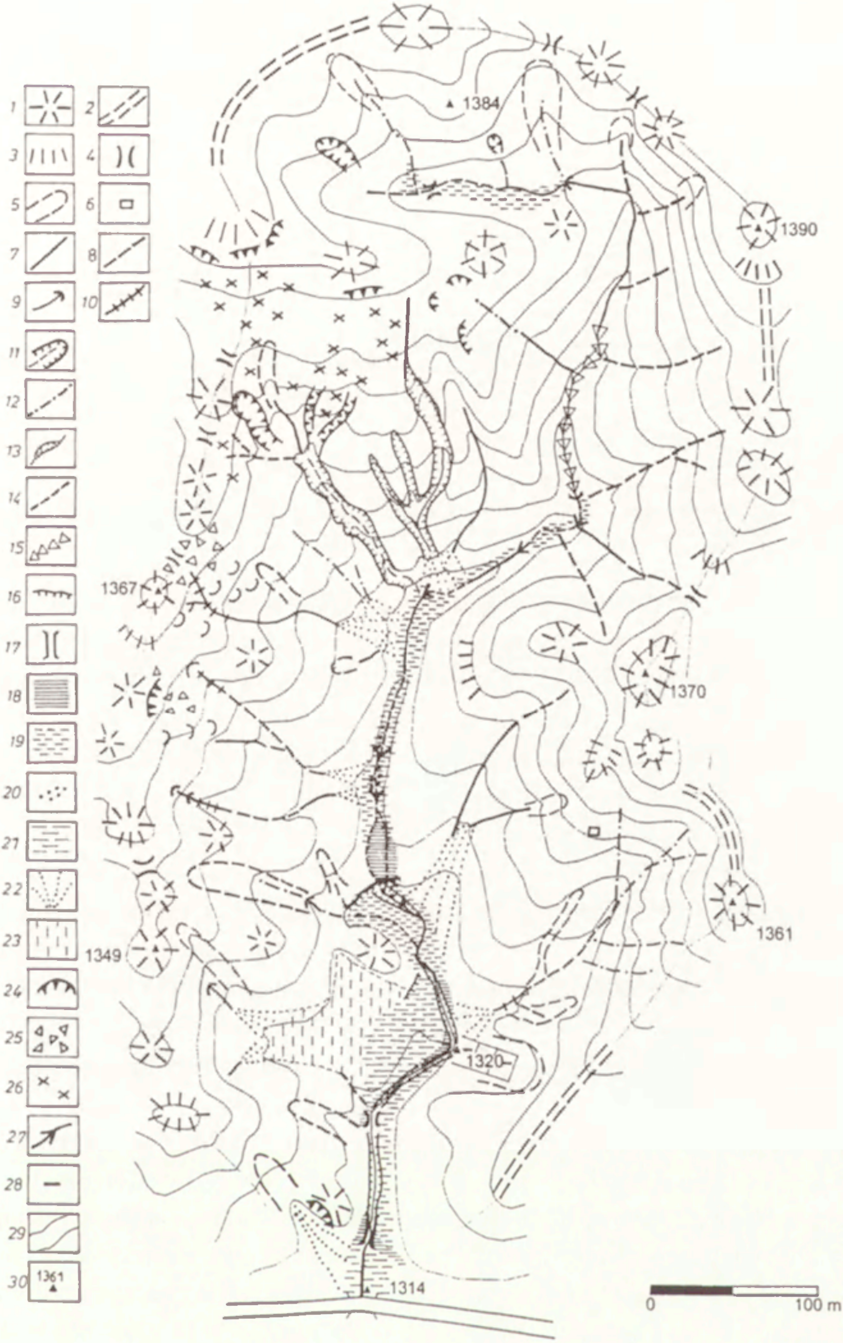
6.2. RELIEF FEATURES

Leszek Starkel

The catchment is dissected by one main valley, which drains to the south (Fig. 13 and 14). The course of the valley is clearly controlled by system of joints that are aligned mainly along N–S and NEE–SWW directions. The relief energy does exceed beyond 30 m in uppermost part, increasing from 40 to 60 m in the middle part and declining again from 20 to 40 m at the base. Tributary valleys are usually 100 to 200 m long. They have various shapes and are dissected – deeper in some places and shallower somewhere else with slopes of 150–250 m long. Drainage network density with main creek together is noticed to be very high, exceeding 4,000 m (i.e. 15 km km^{-2}). Therefore, the slopes and interfluves are densely dismembered. There are conical or flattened hum-

Fig. 14. Geomorphological map of Maw-ki Syiem catchment (surveyed by L. Starkel) 1 – peak, 2 – broad ridge, 3 – slope scarp, 4 – pass, 5 – slope niche, 6 – large block, 7 – V-shape valley with outflow, 8 – dry V-shape valley, 9 – spring niche, 10 – gully with rapids, 11 – large active gully, 12 – shallow slope channel, 13 – channel cut in bedrock, 14 – channel cut in alluvia, 15 – channel filled by rock debris, 16 – erosion scarp (with waterfall), 17 – rocky gate (small canyon), 18 – rocky terrace, 19 – flooded plain (with thin alluvial cover), 20 – gravel-sandy bar, 21 – higher terrace, 22 – proluvial fan, 23 – glacis surface, 24 – scarp of quarry, 25 – coarse debris, 26 – abandoned pits, 27 – man-made dam, 28 – water pond, 29 – contour lines, 30 – elevations in meters

Mapa geomorfologiczna zlewni Maw-ki Syiem (zdjęcie terenowe L. Starkel)
1 – szczyt, 2 – szeroki grzbiet, 3 – krawędź stokowa, 4 – przełęcz, 5 – nisza stokowa, 6 – duży blok skalny, 7 – v-kształtna dolinka z odpływem, 8 – sucha V-kształtna dolinka, 9 – nisza źródłowa, 10 – wąwóz z progami, 11 – duży aktywny wąwóz, 12 – płytkie nacięcie stokowe, 13 – koryto wycięte w skale, 14 – koryto wycięte w aluwiach, 15 – koryto zasypane rumowiskiem, 16 – krawędź erozyjna (z wodospadem), 17 – brama skalna (mały kanion), 18 – skalna terasa, 19 – równina zalewowa (z cienką pokrywą aluwiów), 20 – odsyp żwirowo-piaszczysty, 21 – wyższa terasa, 22 – stożek proluwialny, 23 – powierzchnia podstokowa-glacis, 24 – krawędź kamieniołomu, 25 – rumowiska skalne, 26 – wyrobiska górnicze (dawne), 27 – sztuczne zaporki, 28 – staw, 29 – poziomice, 30 – wysokości w metrach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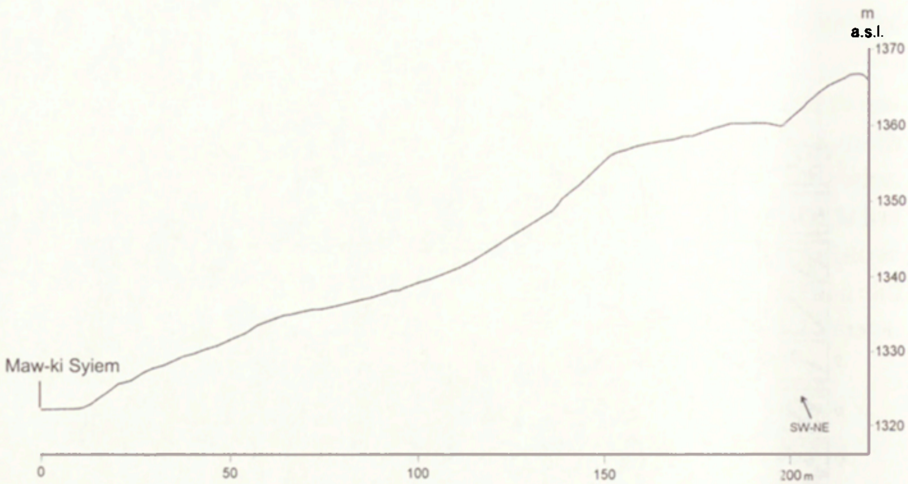


Fig. 15. Slope profile from the ridge between points 1361 m a.s.l. and 1370 m a.s.l. (nivelled by L. Starkel and W. Froehlich)

Profil stoku schodzącego z grzbietu między punktami 1361 m n.p.m. i 1370 m n.p.m.(niwelowany przez L. Starkla i W. Froehlicha)

mocks at every 50 to 100 m which are separated usually by 20° to 30° steep slopes (Fig. 14). The middle parts of the slopes of main valley appears flat (5° to 12° slope gradient, Fig. 15). The lower portions of the valley are either sloping steeply or are convex in its upper part, and going downstream where they extend to the flat areas (2° to 5° slope gradient). These slopes are composed of rocky floors with thin deluvial cover or small proluvial fans of tributaries (Fig. 14).

Relief of the ridges, slopes and valley floors of the main creek has distinct structure-controlled features. The more resistant beds at elevations of about 1,385, 1,365–70, 1,340 and below 1,330 m a.s.l. are expressed in the form of steeper slope segments, hummock's flattening as well as rocky floors of channels and waterfalls together forming regressional terrace steps.

The main valley of Maw-ki Syiem creek starts on the flat surface of about 20–30 m deep with a W–E depression of around 200 m long. This valley is without forests and drained by small creeks. It is cut in the alluvial-deluvial fills up to about 1 m deep (Figs. 16 and 17). This is followed by a long section of deep incision (27 m) with a high gradient (about 38%) indicating a V-shaped feature which reaches upto 200 m long forming a narrow channel filled by large boulders of about 2 m in diameter (Fig. 18). Hence, the average gradient is exceeding 10%. These parts of the steep valley are fully forested (cf. Starkel and Patkowski in print).

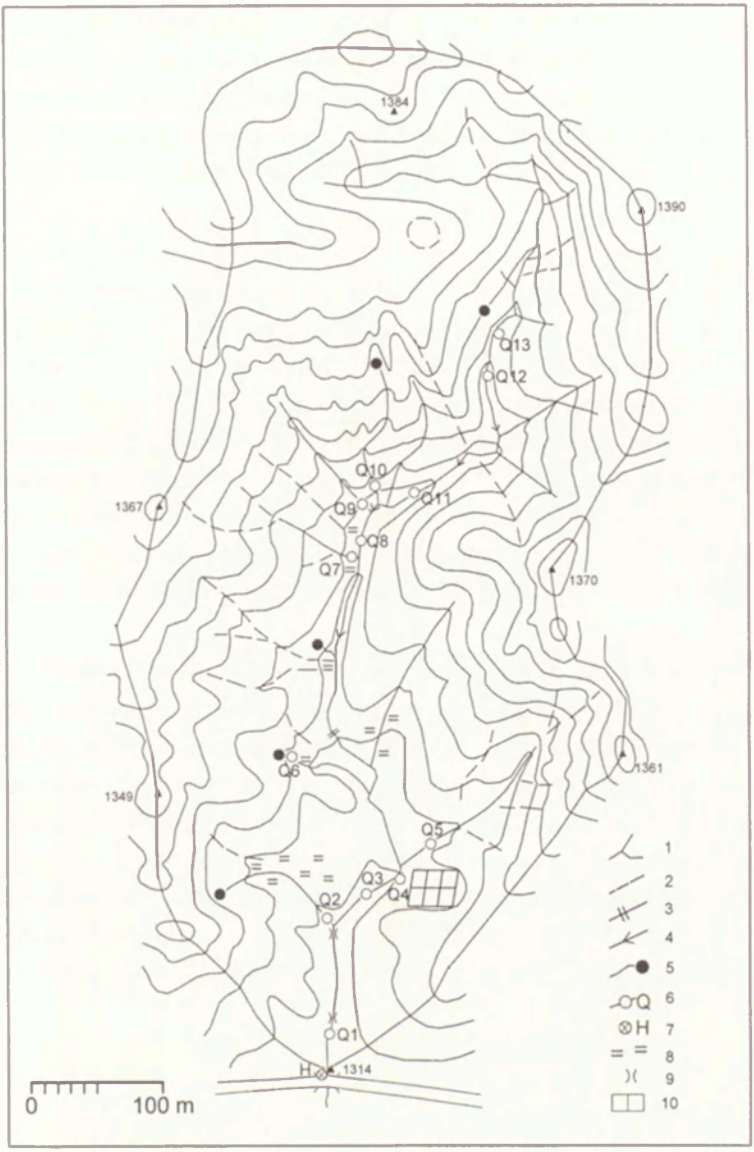


Fig. 16. Hydrographic map of Maw-ki Syiem with discharge measurement points (compiled by L. Starkel and B. Patkowski, in print)
1 – permanent creeks, 2 – periodic creeks, 3 – waterfalls, 4 – artificial barrage, 5 – spring active in post-monsoon time, 6 – measurement points of discharge, 7 – watergauge, 8 – swampy area, 9 – narrow gorge, 10 – pond

Mapa hydrograficzna zlewni Maw-ki Syiem z zaznaczonymi punktami pomiaru przepływu (oprac. L. Starkel i B. Patkowski, w druku)
1 – cieki stałe, 2 – cieki okresowe, 3 – wodospad, 4 – sztuczna zaporka, 5 – źródło czynne w okresie pomonsunowym, 6 – miejsca pomiaru przepływu, 7 – punkt wodowskazowy, 8 – obszar podmokły, 9 – wąski wąwóz, 10 – staw

The next reach starts with the junction of several right-side gullies which delivers a large amount of sandy and gravelly load. The several constructed concrete dams are partly deposited by sand assuming the shape of channel bars (Photo 9). This reach of about 300 m long has a gradient of nearly 25%. It ends with a rocky channel floor of about 40 m long and bordered by 3–4 m high waterfall.

Around the waterfall and downwards, there are erosional holes followed by several meters long gravel bars where incision starts again up to 1 m (first in the alluvial and then ends in the sandstone beds) (Fig. 18). This reach is 180 m long with a gradient of 3.3% and then it turns to the last section which is built of massive sandstone. The river channel is mostly 5 to15 m wide in the lower part of the catchment but reduced to between 5 to or 20% during dry seasons. The lower portion of the catchment is generally sloping with a gradient of 4% up to the narrow section of about 2 m deep with erosional holes separated by flat segments. This is a second regressional step in the valley floor forming a base level for evolution of slopes and tributary valleys in the lower part of catchment.

Drainage density of the permanent streams in the catchment is relatively high as it exceeds up to from 6 to 7 km km^{-2} (i.e. little lesser than 50% of the total drainage network, Fig. 16). But the discharge is rather very low in November and probably before the rainy season when most of the small tributaries dry out (Fig. 16). Besides the main creek and several tributaries, some springs of small discharge can be observed. Only the springs by which water is supplied through deeper groundwater resource in the active gullies that drain out the south-exposed slope in the middle portion of the catchment have the highest discharge rate.

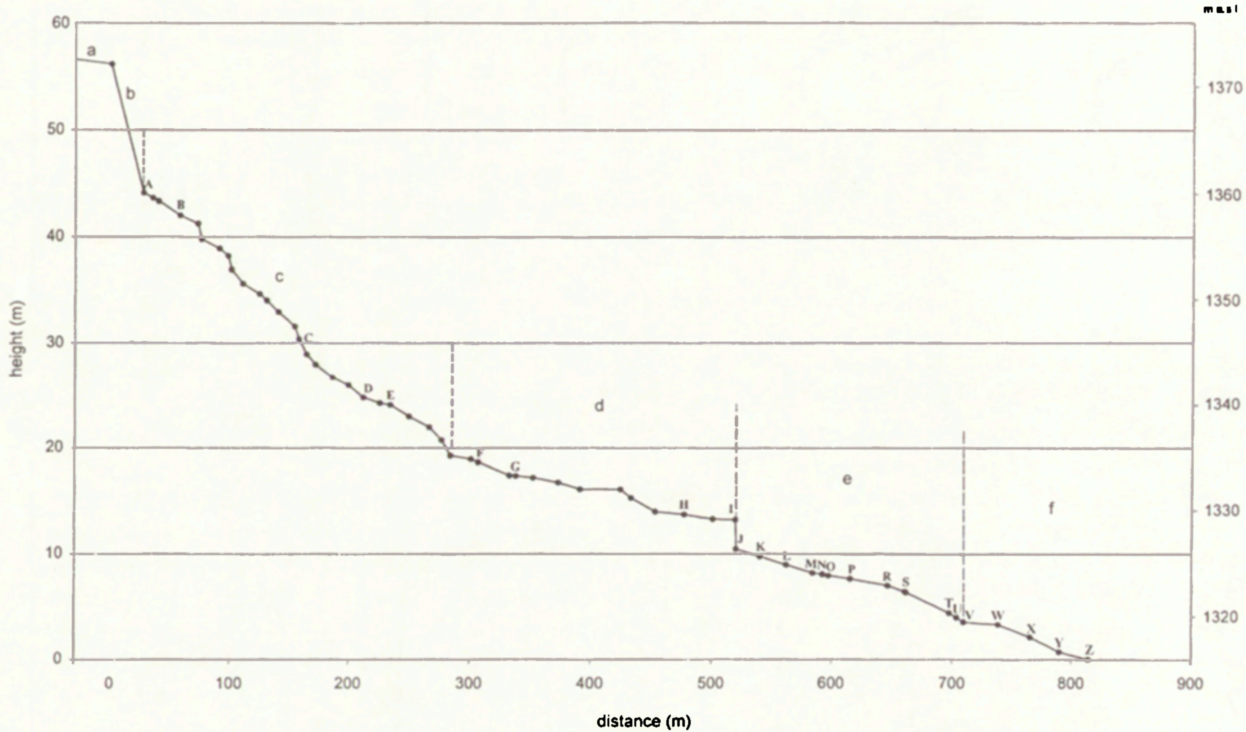


Fig. 17. Longitudinal profile of Maw-ki Syiem creek (after L. Starkel and B. Patkowski, in print)
Profil podłużny potoku Maw-ki Syiem (wg L. Starkla i B. Patkowskiego, w druku)

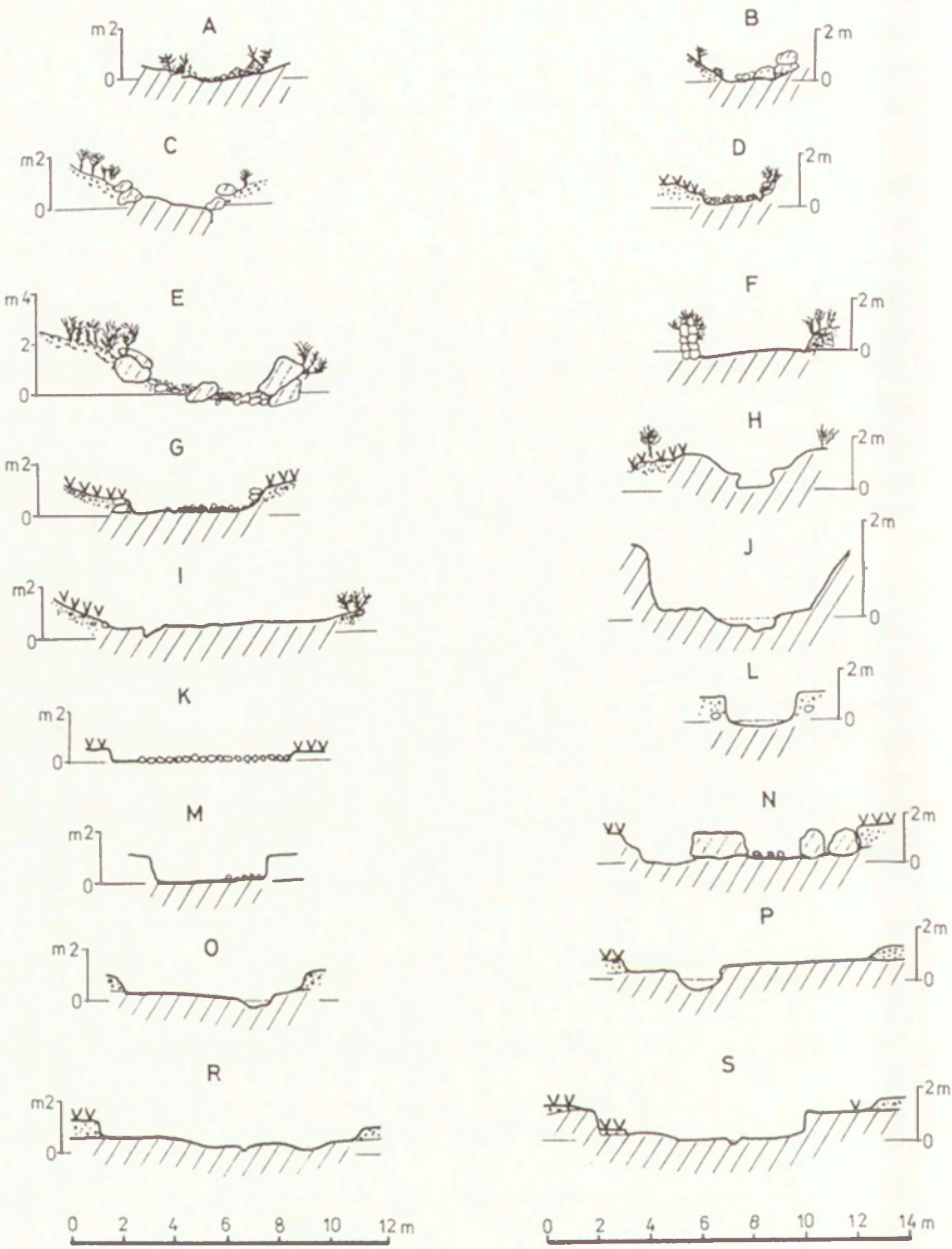
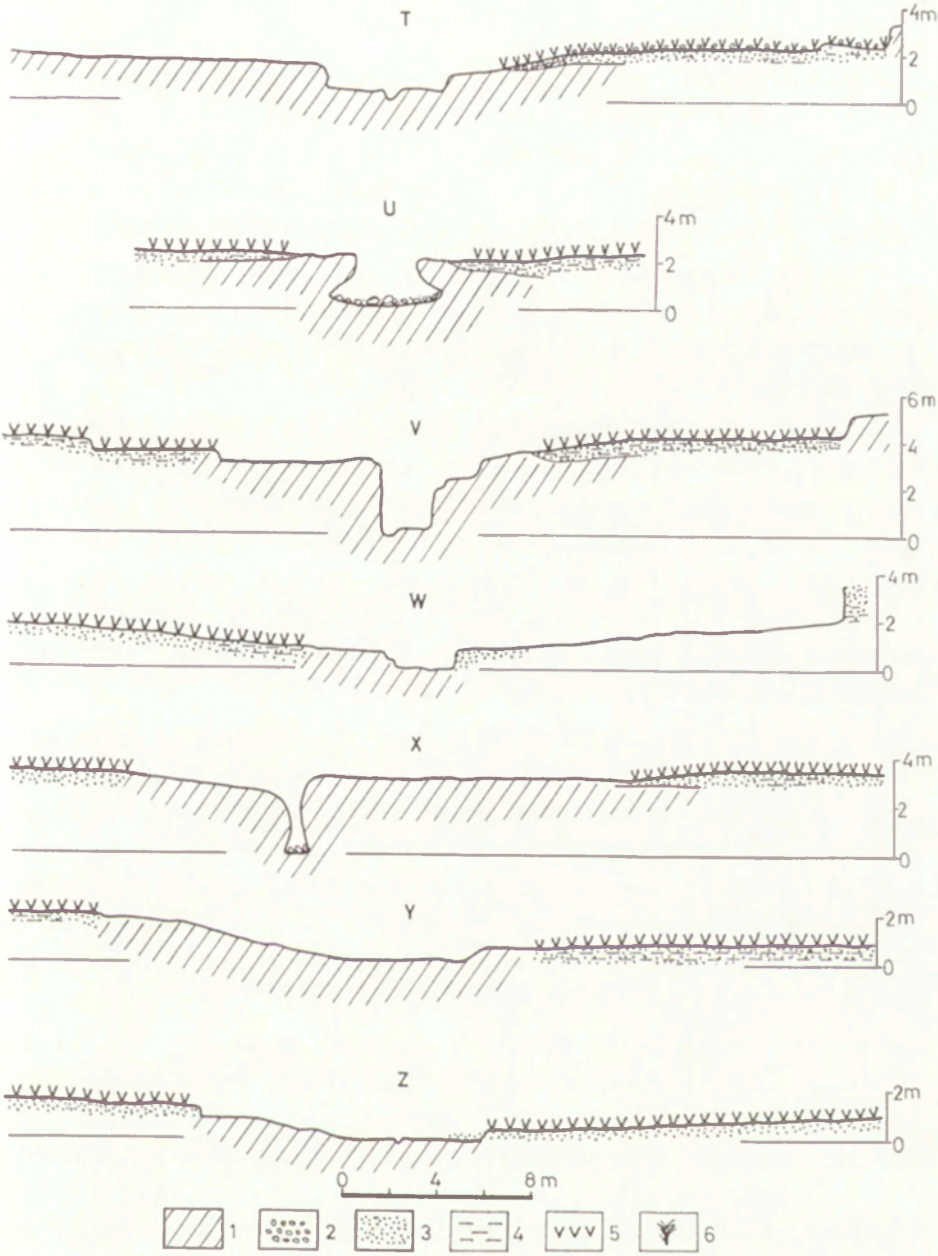


Fig. 18. Transects of Maw-ki Syiem creek channel indicated on the longitudinal profile (after L. Starkel and B. Patkowski, in print)
1 – bedrock (mainly horizontally bedded), 2 – gravel, 3 – sand, 4 – silt, 5 – grasses, 6 – shrubs and trees



Przekroje koryta potoku Maw-ki Syiem zaznaczone na profilu podłużnym (wg L. Starkla i B. Patkowskiego w druku)
1 – skała (zwykle horyzontalnie warstwowana), 2 – żwir, 3 – piasek, 4 – pył, 5 – trawy, 6 – krzewy i drzewa

6.3. THE SOILS

Wojciech Froehlich

Prevalence of shallow and strongly compacted degraded soils is a characteristic feature of the Maw-ki Syiem catchment. Thickness of the soil is observed to be very low ranging from 0.25 to 1.5 m. In many places, the washed waste cover may be seen. Their characteristic features are different as regards the thickness as well as the physical properties depending on the relief.

The organic matter is practically absent in the superficial layers with values ranging from 1 to 7 %. In the forest areas, there exists a very thin layer of Ao horizon (ca. 5 cm). The nutrients are totally washed away leading to acidic reaction in soils (4.5 to 4.9 pH values).

Soil thickness on the flat top of the ridges is noticed to be negligible varying from 35 to 95 cm. Consequently, the subsoil or sandstone bedrock is exposed in some places. On the ridges and also on the steep slopes segments, thickness of the soil tends to decrease rapidly due to the extraction of loamy soil horizons which are used as a raw material for cement manufacturing. Thinness of the degraded soils, a characteristic of the washed waste cover may be seen in the headwater part, whereas the recently cultivated south-eastern part of the catchment has a soil thickness of up to 95 cm.

Thickness of the soil on the slopes varies significantly from 10 to 65 cm. The variability of thickness of the washed waste is generally caused by the degraded soils in the longitudinal slope profiles and is connected with slope gradients. Especially, the convex parts of the sandstone bedrock or subsoil are exposed. Along the headwater sections with steep degraded slopes the washed coarse grain waste occurs which covers up to 40 cm thickness. The waste material is often lacking in the horizon A and B while debris cones occupy the base of the slopes.

The characteristic feature is the widespread occurrence of surfacial layer of compact armouring debris (Photo 10). These resistant pavement layers with debris of diameter up to 5 cm are poorly permeable. The particles of pavement decrease with depth. In this layer, the clayey fraction does not usually exceed 28% of the total weight. Their contents are increasing with depth up to 43%. In general, high percentage of the sandy and coarse particles reaching up to 85% is the characteristic feature of grain composition (Photo 11). The grain size composition and texture of soils lead to poor permeability of the whole profile (cf. Fig. 27).

Photo 9. Water pipes draining the middle part of Maw-ki Syiem catchment rich in water (R. Soja)
Rury drenujące środkową część zlewni Maw-ki Syiem bogatą w wodę (R. Soja)

Photo 10. Remains of lateritic colluvial deposits with the coarse grained armoured top layer (L. Starkel)
Resztki laterytowych pokryw koluwialnych uzbrojone wierchnią, gruboziarnistą warstwą (L. Starkel)

Photo 11. Residual armoured topsoil built up of iron concretions and sandstone fragments, with sparse grass cover (P. Prokop)

Rezidualna wierzchnia warstwa uzbrojona konkrecjami żelazistymi i okruchami piaskowca z rzadką pokrywą trawiastą (P. Prokop)

Photo 12. High water level of Maw-ki Syiem upstream of main bridge after rains in July 2002 (by R. Soja)

Wysoki poziom wody potoku Maw-ki Syiem powyżej mostu po opadach w lipcu 2002 roku (fot. R. Soja)

The foot of the slopes extends over a very narrow zone of the sandy-silty deluvial deposits up to 70 cm deep with the horizons of various contents of clay of about 25 %. In the valley floor, over the impermeable sandstone beds occur the moist shallow sandy-silty alluvial deposits. In the lower reach of the catchment, the silty – sandy deposits up to 120 cm thick occur directly on the bedrock or on gravel deposits.

Only 16% of the total catchment is covered by forest and shrub. Most of the surface is occupied by more or less dense grass cover.

7. THE RAINFALL CHARACTERISTICS

Roman Soja, Surendra Singh

7.1. THE RAINFALL

The total annual rainfall in excess of 10,000 mm is noted at several sites over the globe, but they are generally connected with the monsoonal circulation over the mountain ranges or isolated high peaks. On the southern parts of the Meghalaya plateau where many spurs of different sizes (including Cherrapunji spur) exist, the monsoon conditions are favourable to precipitate heavy rains on the margins of flat surfaces of these spurs which are formed by the steep escarpments and seperated by the canyons of about 1,000 m deep formed in the lower courses of rivers falling from the plateau. Such southern edges of extremely high rainfall are at an elevation from 1,300 to 1,400 m a.s.l. where Cherrapunji and Mawsynram are located.

In the geography textbooks and atlases, Cherrapunji (25°14'N and 91°44'E) has been known since centuries as a place with the highest annual rainfall over the globe. However, as per the meteorological daily records of 10 years (during 1980's) for the Mawsynram station located about 15km to the west (25°18'N and 91°35'E) and at an altitude 100 m higher than that of Cherrapunji (1,401 m a.s.l.), the annual totals of rainfall are recorded higher in the former. According to the rainfall statistics provided by IMD, Regional Office, Guwahati, the mean annual rainfall at these two stations have been observed as:

Mawsynram – 11873 (mean of 26 years for the period 1953–1979)
Cherrapunji – 11542 mm (mean of 31 years for the period 1941–1979)

Such long sequence of data of varying duration may not be able to show the correct picture of mean annual totals. In order to confirm the same fact, monthly and daily records of rainfall for both the stations for a period of 14 years (1986–2000) have been collected and compared. The records do reveal a difference in the annual rain between these two stations. Mawsynram records a mean annual rainfall of 12,666 mm whereas the mean annual rainfall at Cherrapunji is 12,376 mm. Such a difference of about 290 mm rainfall may be either due to variation in methods of collection of rainfall data by different agencies at different places or due to variations in the elevation of these two stations. However, it may be noted that the difference in annual rainfall is rather insignificant and also that both the areas fall under the same area of heavy rainfall.

Preliminary records from the pluviometer in Thankarang Park located only 850 m a.s.l. indicate the role of vertical gradients.

Comparing Cherrapunji and Mawsynram it should be taken into consideration that station in Cherrapunji belong to the Indian Meteorological Department and has permanent qualified staff and rainfall data are recorded in form of pluviograms. In the station in Mawsynram belonging to the Public Work Department, the observers were changing frequently and some of the noted daily records are problematic.

7.2. CONTINUITY OF RAINFALL RECORDS AT CHERRAPUNJI

It is interesting to note that the mean annual rainfall at Cherrapunji is not similar as referred in the literature concerned (Das 1951; Todd 1970; Singh 1996; O'Hare 1997). The divergence may perhaps be attributed to taking into consideration different reference periods as well as various errors. The first measurement of rainfall at Cherrapunji started in 1850 (Oldham 1854). Since then, the location of the rain gauge had been shifted several times. Throughout many years two stations were operated in parallel. The measurements during the 19^{th} century were not carried out continuously being often interrupted in winters and over a long period of time. Many times the measurements were restricted to the summer months only. More reliable records are available for the period 1903–2000. However, there are several breaks in the measurement particularly in the years 1960, 1961 and 1963 to 1965 due to the lack of reference station.

The unpublished statistics from the Regional Centre, Indian Meteorological Department (RMD), Guwahati present the mean annual rainfall of about 11,314 mm for Cherrapunji during the period 1852–1989. After adding the statistics covering 10 more years (1990–2000) we obtained the rainfall data for a total of 149 years with the mean value of 11,371 mm.

The records available at Indian Meteorological Department, Pune cover the period 1902–2000. After elimination of years with breaks, the mean annual rainfall is calculated at 11,109 mm and is only 362 mm lower than the average annual rainfall of 149 years. In the 20th century, the lowest annual rainfall of 6,283 mm was recorded in 1951 and the highest 23, 663 mm in 1974. The standard deviation is calculated as 2,614 mm. All the above records which are presented especially the lowest value indicates that the mean annual rainfall of 7,640 mm as cited by G. O'Hare (1997) could be an error in calculation.

7.3. ANNUAL AND MONTHLY COURSE OF PRECIPITATION

On account of non-availability of rainfall records at Cherrapunji Station for the 5 years from 1959 to 1965, the tendency of annual rainfall has been interpreted by calculating regression coefficient seperately for two periods of time: a) The early half part of the century (1903–1959) and b) The last- half of the century. This includes the data covering 35 years (1966–2000).

The first part of time series data is characterised by relatively balanced rainfall with less temporal fluctuation. There is a slow increase of annual rainfall during this period (regression coefficient 15.5 mm/year).The second period too shows increasing trend in the annual rainfall (regression coefficient 42 mm/year) which is higher than the earlier period (Fig. 19). However, there is a moderate annual increase of about 16.0 mm/year, if the entire 93 years period is taken into account.

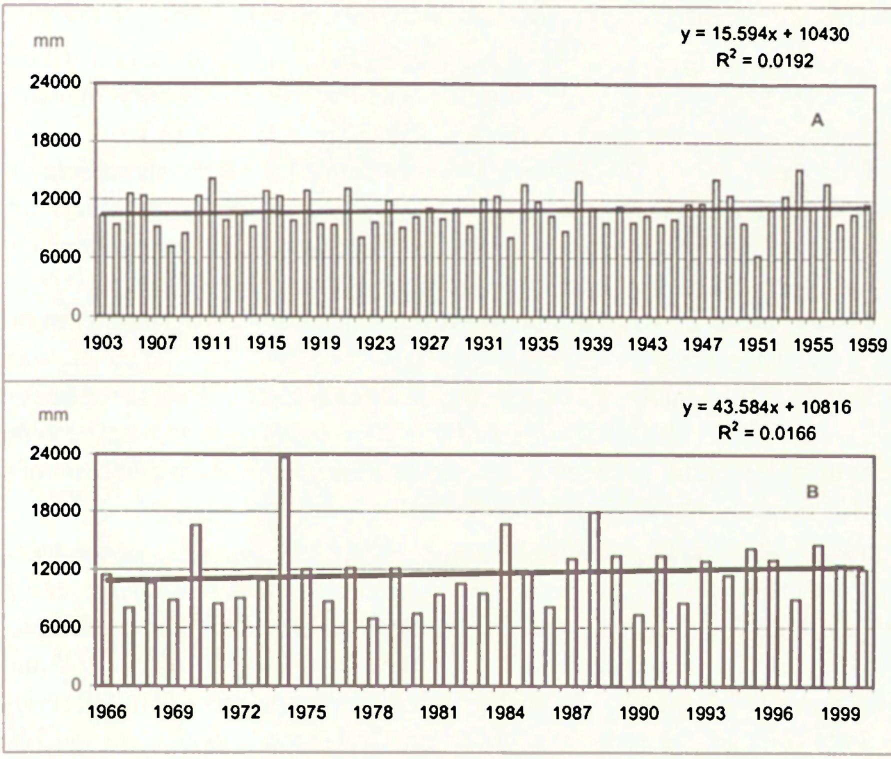


Fig. 19. General trend of annual rainfall in Cherrapunji during the 20th century (by R. Soja). A – 1903–1959, B – 1966–2000.

Tendencje zmian rocznych sum opadów w Cherrapunji w XX wieku (oprac. R. Soja). A – 1903–1959, B – 1966–2000.

Table 7. Annual rainfall data available for Cherrapunji

Annual rainfall (mm)	No. of years	Duration	Source
11 314 (mean annual)	136	1852–1989	Unpublished records from RMD Guwahati
11 371 (mean annual)	149	1852–2000	-do-
11 109 (mean annual)	94	1902–2000*	IMD Pune
6,283 (lowest)	1	1951	IMD Pune
23,663 (highest)	1	1974	IMD Pune

*Except 5 years break (1960–65)

The fluctuating tendency of rainfall is observed normal during the first period when annual rainfall values are very close to the regressionline. Higher temporal fluctuation is observed in the second classified period for the present study. For example, the extreme cases of annual rainfall have been seen when it crosses the 15,000 mm rainfall as well as the 8,000 mm rainfall values. It occurred as many as five times in the second – classified period of the analysis. In this context, it may be noted that two years are recorded to be exceptionally wet as rain precipitated 23,663 mm in 1974 and 22,990 mm in 1861.

On account of the monsoonal character of rainfall, Cherrapunji receives most of its share during the summers. June, July and August are the months of heavy rainfall which account for nearly two-third share (63%) of the total annual rainfall received (Fig. 20). After WMO publication (1984) the summer monsoon in Cherrapunji sets in around 29 May and continues till early October. O'Hare (1997) cites almost the same dates of the onset and end of the monsoon period. The amount of rainfall received during this period is about 8,600 mm in 130 days, (i.e. 77% to the total annual rainfall). The start of summer monsoon is accompanied by heavy rain ranging from 100 to 300 mm per day and ends with less intensity of 20 to 50 mm/day. But sometimes, there are heavy rains of more than 100 to 300 mm/day during the monsoon period. Similar trend of monthly precipitation of summer rains has been recorded at other stations in Meghalaya plateau Tura and Shillong.

During the month of May, before the starting of the summer monsoon, occasional rains for 1 to 2 days long have been recorded with rainfall exceeding 500 mm in 24 hours but it does not relate to monsoonal circulation. For example, 505 mm rainfall was recorded on 5^{th} May 1999, 450 mm on 23^{rd} April 1995 and 644 mm on 16^{th} April 1990. Year after year these months record rainfall series of 3 to 5 days long duration with total rainfall ranging between 500 and 700 mm which only adds to the relatively high rainfall totals. On the contrary, the mean monthly precipitation during the post Monsoon period from November till February varies from 14 to 64 mm only. However, there are rain free months during the dry winters with occasional heavy rains repeating every 3 to 4 years.

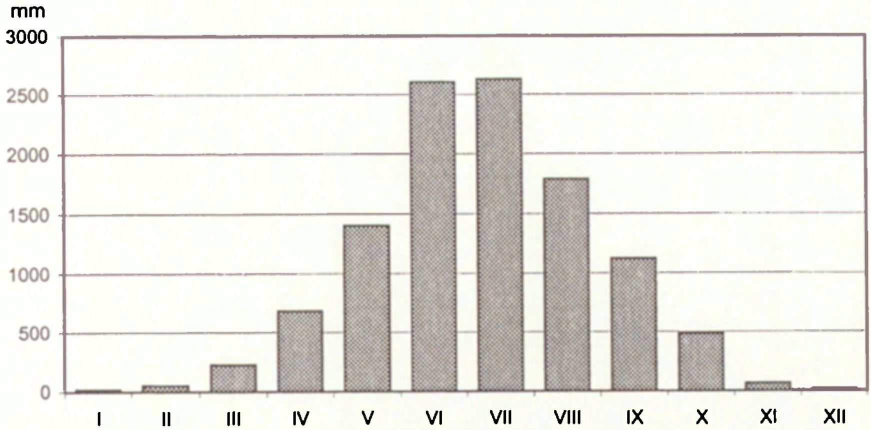


Fig. 20. Mean monthly rainfall at Cherrapunji 1902–2000
Średnie miesięczne opady w Cherrapunji (1902–2000)

7.4. NUMBER OF DAYS WITH RAINFALL

The definition of a rainy day given by the Indian Meteorological Department, Pune (2.5 mm and above), differs from the European Standards where a 'rainy day' is considered to be the total rain of 0.1 mm received in a day. Following the IMD, Pune definition, the mean number of rainy days is counted 159 days if 13 years (1986–1999) daily rainfall data are considered. However, there is a noticeable decline in the number of rainy days during the 20th century. It amounts to around 8 days per year where regression coefficient is calculated at – 0.0857 per year in the long series of monthly data. In the temporal series of fluctuation, the number of rainy days varies from the highest of 180 to the lowest of 125 days with a normal variation of about 6.79%.

Monthly variation in the number of rainy days is significant. During dry season, from December to March, they vary from 1 to 16 days and during premonsoon month of May; it reaches up to a total of 22 days. The Month of July is full of rainy days, when 28 out of a total of 31 days are recorded as rainy days. In spite of the highest number of rainy days in July, the highest per day average rainfall is recorded in the Month of June (Table 8). It means that the rainfall totals are higher in June than in July by 10%.

Table 8. Mean monthly precipitation (mm), number of rainy days and mean daily rainfall in Cherrapunji (1902–2000)

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec	Total
Mean rainfall	20	52	227	685	1405	2608	2632	1791	1126	485	64	14	11109
Min.	0	0	6	74	153	475	448	260	61	4	0	0	6283
Max.	205	577	1429	1845	3961	5832	8247	4659	4661	1876	390	244	23 663
Number of rainy days	2	3	7	16	22	25	28	25	19	9	2	1	159
Intensity mm/day	10	17	32	43	64	104	94	72	59	54	32	14	–

N. B.: The number of rainy days are calculated according to IMD Pune norms. The day of more than 2.5 mm of rainfall is considered as rainy day

7.5. RAIN STORM CHARACTERISTICS*

a) Criteria for identification of stormy days

There are numerous studies on the estimation of extreme rainfall conditions (Maheras, Kolyva-Machera 1990; Mooley, Parthasarathy 1984). A long time-series rainfall data of 100 years or more was compiled and its mean and standard deviations were computed to find out extreme conditions of rainfall characteristics of Eastern Mediterranean region in Europe. The dry/wet years were identified by using Standard Score Technique of the distribution (Kutiel et al. 1996). A significant exercise of estimating extreme Indian monsoon rainfall was made by D.E. Reeve (1996) to test the validity of various statistical tests of rainfall distribution, considering time series data of 306 well-distributed rain gauge stations in India for a period of 120 years (1871–1991). D.E. Reeve (1996) calculated best-fit distribution parameters for various families of rainfall distribution: normal, log-normal, gamma, exponential, Gumbel and General Extreme Value (GEV) distributions and concluded that GEV distribution should give 'best-fit' results.

It may be noted here that the dimensions and time-series data for the present study are based on the daily rainfall records and hence are different from the above studies. A simple criterion of 'standard z score' for identifying the stormy days has been adopted for the present study. There are two main steps of the procedure for identification of stormy days. These are:

a) According to the definition given by Indian Meteorological Department (IMD) Pune and its standard classification for the wet days, a day is considered rainy day when it receives an amount of rainfall equal to or more than 2.5 mm. A significant temporal fluctuation is seen from the distribution of total rainy days of above 2.5 mm daily in Cherrapunji. The year 1986 was recorded as low-magnitude year since it recorded only 60.6 mm rainfall per rainy day. On the other hand, rainfall of about 116.62 mm per rainy day with moderate number of rainy days (i.e., 158) was recorded in 1988 (Table 9). The degree of annual variation of daily rain of rainy days is recorded more than 100% in each year. It means that there is a significant temporal fluctuation in daily rainfall at Cherrapunji. The higher degree of rainfall variability (CV=195.1%) with moderately high mean rain per rainy day (84.2 mm) was recorded in the year 1995 when the total number of rainy days are enumerated as 169 and the few

* The major text of this section is the modified version of the paper 'Rainstorm Characteristics of Extremely Humid Area of the World – Cherrapunjee' which was presented and discussed by Singh and Syiemlieh in 'International Conference on Forecasting Monsoon from days to years' India Habitat Centre, New Delhi, and 21st – 26th March, 2001.

Table 9. Temporal fluctuation in annual rainfall, number of rainy days and DAER in Cherrapunji in the years 1986–1998

Years	No of rainy days (n)	Total rainfall above 2.5 mm daily (Σx_i)	Mean rain per rainy day (in mm) ($\bar{x}$)	S.D. (σ)	C.V. (%) ($\sigma / \bar{x}$)	Stormy rain (above DAER norm)		No of stormy days
						Total	%	
1986	148	8967	60.6	94.5	156.0	5101	56.9	33
1987	165	13234	80.2	114.2	142.4	9476	71.6	47
1988	158	18427	116.6	150.2	128.8	15294	83.0	61
1989	163	13579	83.3	105.2	126.3	10294	75.8	52
1990	171	12808	74.9	125.4	167.4	7716	60.2	43
1991	169	13513	80.0	88.6	111.3	10271	76.0	54
1992	142	9676	68.1	100.9	148.2	5324	55.0	31
1993	166	13067	78.7	108.4	137.7	9970	76.3	52
1994	151	11445	75.8	95.8	126.4	7857	68.7	41
1995	169	14232	84.2	164.3	195.1	11474	80.6	43
1996	153	12868	84.1	107.0	127.2	10091	78.4	51
1997	156	8940	57.3	85.9	149.8	5664	63.4	28
1998	152	14528	95.6	112.3	117.5	11325	78.0	55
Average	159	12714	80.0	111.7	141.1	9220	71.1	45

days having extreme conditions as was the case on the 15th and 16th of June of this year received the highest rain during the last 13 years. It raises the coefficient of variability for this year.

b) The Daily Average Effective Rainfall (DAER) is the criteria for identifying stormy days. The entire domain of daily rainfall data of rainy days is transformed into standard z scores as $z = [(x_1 - \bar{x}/\sigma]$ where x_1 is the rain of a day, x = the mean and σ = the standard deviation of daily rain for 13 years. In fact, $\bar{x}$ must determine the normal wet days when z =0 (80.0 mm; total number of days are counted 652 during study period of 13 years). The range of positive z scores is classified into four categories, namely, (i) the Stormy Days as $z \leq .05$ (above 85.9 mm daily rainfall; total number of days are counted 591), (ii) the Heavy Stormy Days as $z \leq 50$ (above 137.8 mm; total 355 days); (iii) the Very Heavy Stormy Days as $z \leq 1.50$ (the days receiving more than 253.1 mm rainfall; total 132 days) and (iv) the Extremely Heavy Stormy Days as $z \leq 2.50$ (days receiving more than 368.4 mm of rain; the total number of days are counted as 54 only during the period of 13 years). Thus, the days, which receive more than 85.8 mm of rain, are considered as stormy days in the domain of the present study. The magnitude and share of total stormy rain also fluctuate temporally as the years 1988, 1989, 1991, 1995, 1996 and 1998 were considered the extreme stormy rain years when total amount of stormy rain was recorded more than 10,000 mm, which accounts for more than 75% of total annual rainfall.

7.6. RAINFALL INTENSITY

The intensity of rain expressed in millimetres per time unit is one of the most important parameters. It controls the start and rate of overland flow and following soil erosion and therefore is one of the basic parameters used in formulas describing the slope wash.

Standard measurements of rainfall totals are made once per day. In the Indian publications the rainfall intensity per hour is evaluated by division of rainfall total in one or several consecutive days per 24 hours (Table 10, Singh, Syiemlieh 2001).

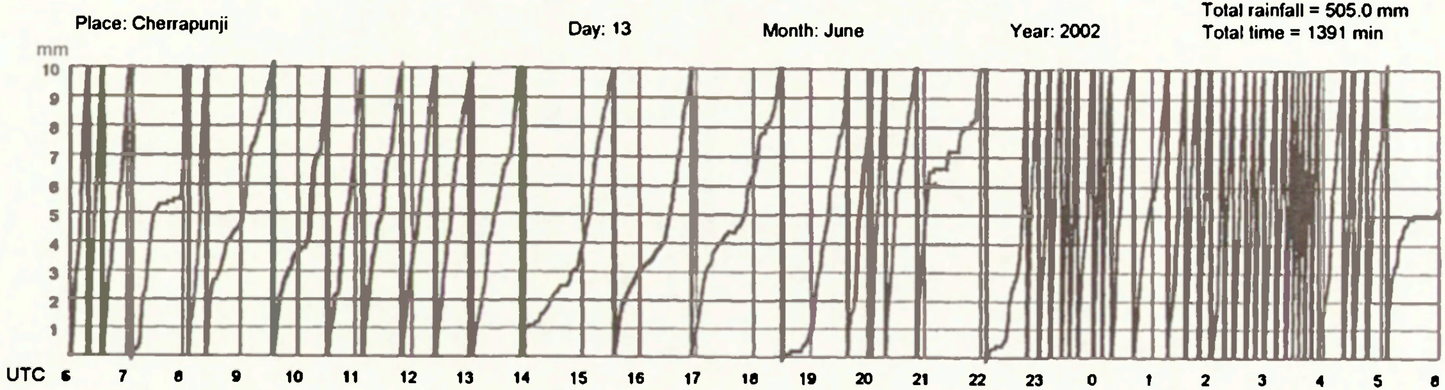
Table 10. The magnitude and intensity of rainfall for six major storms in Cherrapunji

Period of storm	Year	Duration (days)	Total precipitation (mm)	Average intensity (mm/hr)
21–29 August	1988	9	3038.9	14.1
14–17 June	1995	4	3017.1	31.4
2–11 July	1988	10	2827.9	11.8
5–11 June	1998	7	2278.6	13.6
21 July–1 August	1987	12	2259.0	7.8
29 June–6 July	1993	8	2074.4	10.8

But very rarely the rain is continuing throughout full 24 hours. Generally day before or after the day with the highest totals the real time rarely exceeds 12 hours. The internal structure and daily course in Cherrapunji is very complicated. The high intensity rain starts usually during evening hours and continues till morning. Between 10 and 20 hour appear mainly short showers of low intensity.

The correct data of rainfall intensity may be obtained only from continuous pluviographic records. The applied by use in Cherrapunji pluviometer SEBA (made in Germany) has time division only 1 second. It is registered every 0,1 mm of rainfall. Following the producer's instruction in the calculation by computer program were taken 12 minute (720 sec) units. In case of distance between impulses longer than 12 min, this time is not recorded as the rainfall. The first published records of rainfall intensity in Cherrapunji show the presence of intensities 40–70 mm/hour (Starkel at al. 2002). Such intensities are recorded many times every year. It may be expected higher intensities, especially during days with rainfalls above 500 mm, appearing almost once every year.

As an example it has been elaborated one rainy course 10 days long in 2002 when between 12^{th} and 21^{st} June it was recorded 2159,7 mm with the highest daily rain 505 mm (Fig. 21). The hourly intensities are presenting on Figure 22.



rainfall	29.2	7.3	18.1	9.1	13.7	16.1	15.9	11.6	2.9	9 2	7.8	5.4	4 6	16.5	27.1	5.4	19.7	52 5	33 5	33 5	52 4	70 0	35.7	7 8
time	60	60	60	60	60	60	60	60	60	60	60	60	48	60	60	46	60	60	60	60	60	60	60	37

Fig. 21. Pluviometric registration of extreme rainfall on 13 June 2002 (by R. Soja)
Pluwiometryczny zapis ekstremalnego opadu z 13 czerwca 2002 (oprac. R. Soja)

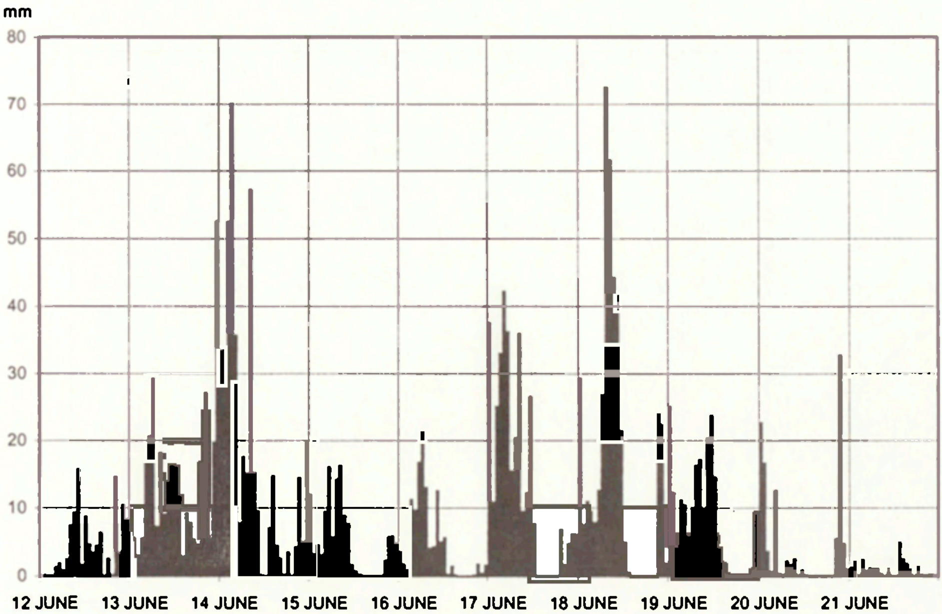


Fig. 22. Rainfall intensity (mm per hour) during continuous rains from 12 to 21 June 2002 (by R. Soja)

Natężcnie opadu (mm na godz.) w czasie rozlewncgo deszczu w dniach 12–21 czcrwca 2002 (oprac. R. Soja)

During 240 hours of these 10 days it was raining during 179 hours e.g. 75% of hours. The real duration of rainfall measured in minutes was 8479 min. That is 59% of time. Table 11 presents the duration of rainfall intensities during these 10 days after calculation of rainfall during each 179 hours. Then all hourly records were divided into classes 10 mm each. In every class the time in minutes served to calculate the real intensity in mm/min. The relation between rainfall totals and intensity is presented by curve (Fig. 23), described by regression equation;

$$Y = 0.0162x - 0.0693, \quad R^2 = 0.9977$$

where:

y – means intensity in mm/min; x – rainfall total in mm

Figure 22 shows a complicated temporal structure of rainfalls. It is not easy to distinguish the compact rainy series. Only on 13 and 14 July it was raining continuously, during the other days it followed a daily course, typical for Cherrapunji, with breaks during the noon hours. The highest intensity per hour 72.5 mm (1.21 mm/min) was recorded on 18 June. These high intensities determine the rainfall totals. 23 % of the total value precipitated during only 5% of time.

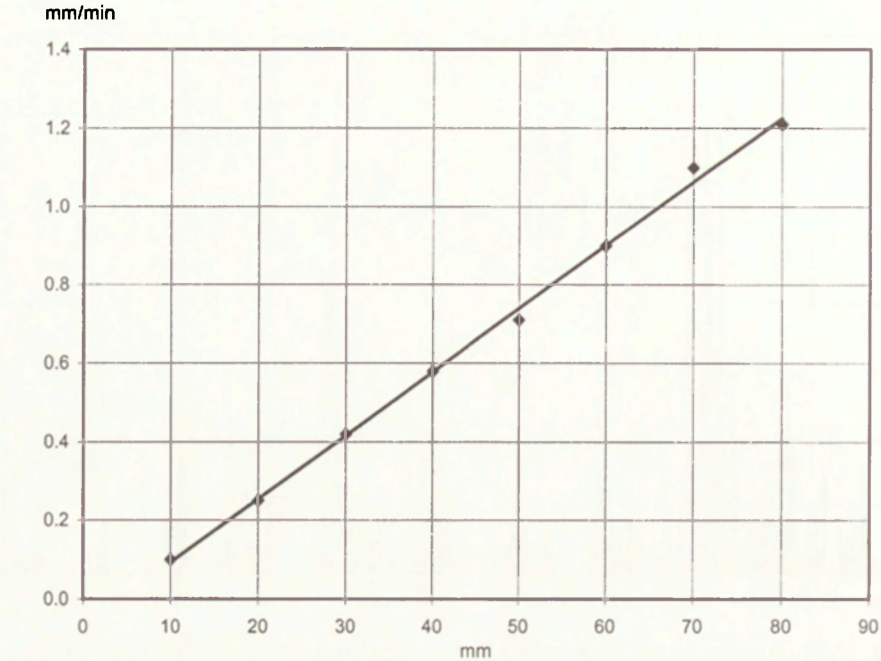


Fig. 23. The relationship between a total of highest rainfall and rainfall intensity in Cherrapunji (by R. Soja)
Związek między najwyższymi opadami a intensywnością opadu w Cherrapunji (oprac. R. Soja)

Table 11. Duration of variations in rainfall intensity during 12–21 June 2002

Intensity classes (mm/hr)	Totals (mm)	Duration (min)	Intensity (mm/min)
>70.1	72.5	60	1.21
60.1-70.0	131.5	120	1.10
50.1-60.0	162.1	180	0.90
40.1-50.0	128.1	180	0.71
30.1-40.0	278.0	480	0.58
20.1-30.0	385.5	916	0.42
10.1-20.0	550.3	2221	0.25
<10.0	450.4	4317	0.10

In the collected records from the years 1999–2002, till now elaborated only in minor part, have been found rainfalls about 1 hour long, with intensities passing 100 mm/hour what amounts to 1.7 mm/min. In shorter time intervals even much higher intensities may be expected. On table 12 are presented the intensities for intervals from 30 sec. to 24 hours, recorded during the above described rainfall course from 12th to 21st June 2002. During intervals one or several minutes long the intensities are closely to 2.0 mm/min. The highest recorded intensities for one hour reached 1.22 mm/min. The highest rainfall in 24 hours during these 10 days reached only 0.35 mm/min. The analysis of the all gathered records should help in the future to formulate an equation describing the relationship between duration of the rainfall and its intensity.

The records from Cherrapunji are cited many times as the examples of the highest rainfalls in the global scale (cf. Todd 1970; Chow Ven Te et al. 1988). But these are the records from the period 1850–1950. After 1950 the rainfall totals have increased. Therefore these data have been introduced to the former table. On the table 13 all these changes are visible and source of this information is mentioned.

As the highest daily rainfall was taken 1563 mm recorded on 16 June 1995 in Cherrapunji. The other extreme daily totals are much lower:

14 June 1876 – 1036 mm

12 July 1910 – 998 mm

5 June 1956 – 974 mm

15 June 1995 – 930 mm

Especially interesting are the clustering of 2-day rainfall reaching 2493 mm, as well old monthly record 9300 mm from July 1861. Also a new annual record 23 663 mm should be noted.

Table 12. Highest rainfall intensities in different time units

Duration	Rainfall depth (mm)	Intensity (mm/min)
30 sec	1.0	2.00
1 min	1.8	1.80
10 min	16.3	1.63
30 min	46.3	1.54
1 h	72.5	1.21
24 h	505.0	0.35

Table 13. Highest rainfall of various duration in Cherrapunji in the period 1850–2000

Duration	Depth (mm)	Period	Source
1 day	1563	16.VI.1995	RMD, Gauhati
2 days	2493	15–16.VI.1995	IMD Poona
5 days	3100	14–18.VI.1995	IMD, Poona
15 days	4 798	24.VI–8.VII.1931	Todd, 1970
31days	9 300	VII.1861	Todd, 1970
2 month	12 767	VI–VII.1981	Todd, 1970
3 months	16 369	V–VII.1861	Todd, 1970
4 months	18 876	VI–IX 1974	IMD, Poona
5 months	20 412	IV–IX. 1861	Todd, 1970
6 months	22 454	IV–IX 1861	Todd, 1970
12 months	23 663	1974	IMD, Poona
2 years	40 768	1860-1861	Todd, 1970

8. RUNOFF GENERATION IN EXPERIMENTAL CATCHMENT

Wojciech Froehlich

The understanding of runoff generation and soil erosion processes in the Maw-ki Syiem catchment is directly related to the intensity and depth of extreme rainfall, the infiltration into the ground and the routing of excess rainfall as overland and linear flow flux to channel system during summer monsoon season. An observation of stream flow fluctuation indicates that the falling stages of peak discharge are very sharp and go on for a very short time during rainy seasons. It reflects limited retention capacity of soils and important role of surface flow in runoff generation.

Measurements of infiltration rate on different times during dry season in November, 2000 were carried out by flooding methods using the Burger's cylinder (compare chapter 3.2.) at down slope profile and in valley bottom of the Maw-ki Syiem catchment.

Figures 24 and 25 show typical relationship between time and depth of infiltration. The soil profile absorbs 100 mm of rainfall during 3 to 4 hours. The results indicate very low infiltration rate both on the slopes and in valley bottom. It is evident that increasing rainfall intensity exceeds infiltration rate. The conversion of precipitation into runoff is mostly controlled by a very small infiltration rate of soil profile. The grain size composition and texture of the waste cover control the differences in the permeability at various depths. The deluvial deposits at the foot of the slope state the horizons of various content of silty-clay fraction, influencing changes of the infiltration rate. Such mechanical composition and physical properties of soil surface have a distinct impact on rapidly overland flow generation and relatively low water capacity (Fig. 26).

It may be assumed with some approximation (as hypothesized) that the threshold of the start of Hortonian saturated overland flow is practically passing through during each rain of the monsoon season. The full-saturated soil profiles were still observed in November, 2000 during the beginning of dry season. During heavy and long lasting rains, the full saturation of the soil profile accelerates the overland flow.

Saturated overland flow and delayed return flow are the characteristic features of the slopes, while the saturated sheet flow prevails at swampy valley bottom. The linear runoff within the gullies and along the paths also plays an

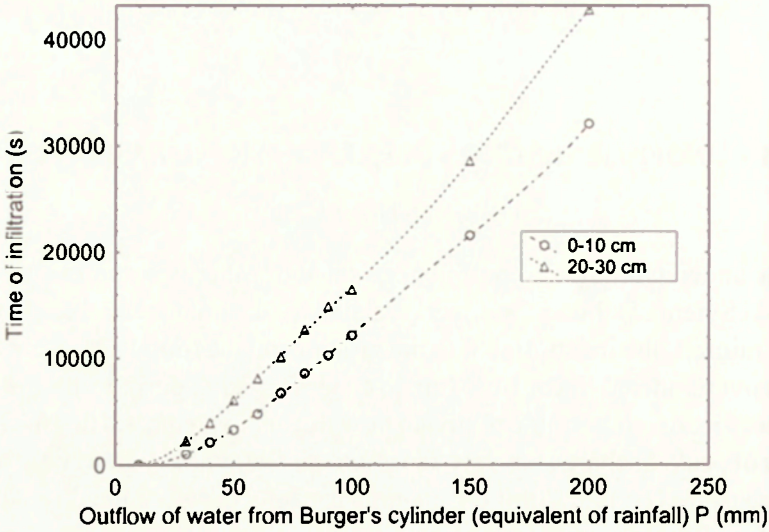


Fig. 24. Sequence of infiltration rate of 200 mm rainfall on the slope of experimental catchment during drought on 10 November 2000 (by W. Froehlich, after L. Starkel et al. 2002)
Krzywa szybkości wsiąkania 200 mm wody na stoku zlewni eksperymentalnej w porze suchej 10.11.2000 (oprac. W. Froehlich, za L. Starkel i in. 2002)

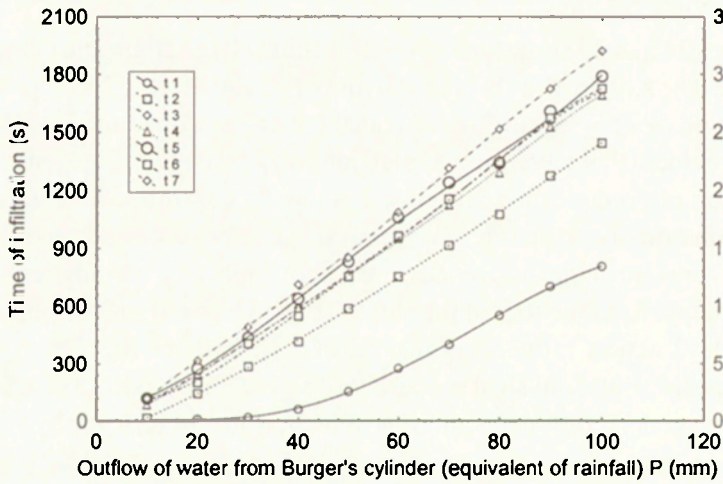


Fig. 25. Sequence of infiltration rate of 100 mm at different soil depth (by W. Froehlich)
Krzywa szybkości wsiąkania 100 mm wody na różnych głębokościach gleby (oprac. W. Froehlich)

important role in the stream flow generation. This is a reflection of rapid rising water stages in the Maw-ki Syiem stream while heavy rains occur (Photo 12).

The water capacity of soils and regolith was determined using the Kopecki's cylinder of 100 cm^3 volume each. Samples were collected in two undisturbed soil profiles up to 1 m depth with intervals of 20 cm. The results show

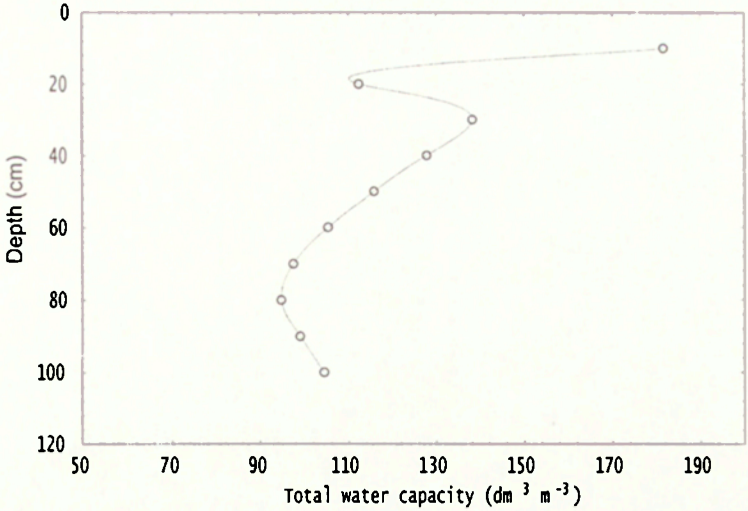


Fig. 26. Total water capacity of soil profile (by W. Froehlich)
Pojemnosc wodna profilu glebowego na stoku (oprac. W. Froehlich)

that the total water capacity changes with the depth being relatively less differentiated to 60 cm depth (Fig. 27). But it decreases by 25 to 40% at 1 m deep and by 50 to 60% at the bottom near the contact with the bedrock. Thicker slope deposits are found in at different water capacity, which are mainly controlled by grain size composition. However, it must be noted that the samples being fewer than desirable, could not provide greater and detail characteristics of changeable water capacity depending on local conditions.

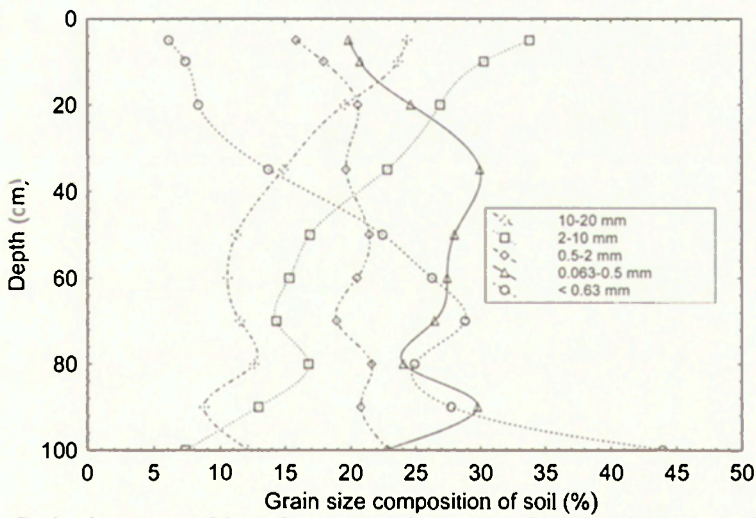


Fig. 27. Grain size composition of representative soil profile, showing coarser fraction of top layer (by W. Froehlich)
Skład granulometryczny reprezentatywnego profilu glebowego, wskazujący na frakcję gruboziarnistą w warstwie stropowej (oprac. W. Froehlich)

9. SOME ASPECTS OF RAINFALL-RUNOFF RELATIONSHIP

Roman Soja, Leszek Starkel, Hiambok J. Syiemlieh

Observations of water level and river discharge in the Maw-ki Syiem creek are very sporadic. Nevertheless, they provide a general picture of the reaction of runoff contributed by rainfall. These records were collected during two contrasting seasons: late autumn, when there was no rain with gradual decrease in the groundwater reservoirs and during the summers of heavy rains.

Measurements of discharge in several cross-sections of main creeks and in several tributaries were carried out by the team consisting of four persons (mainly W. Froehlich, L. Starkel, P. Prokop and H.J. Syiemlieh) using volumetric method on 20th November, 1999, 12th November, 2000 and 24th November, 2001 (Table 14). Discharge of the main creek is observed to be decreasing during the time of measurements because, in the middle part of the valley near small barrages, most of the flowing water is collected into the pipes and distributed to many houses (Fig. 16). Therefore, the transects downstream are less representative (Q1, 3 and 11). At the same time, the upper sites Q12 and Q13 are not levelled because part of the water percolates between the boulders. But the lowest transects clearly show a declining tendency during consecutive years. The drop in discharge was especially distinct in November, 2001.

Measurements of water volume on the small tributaries seem to be more significant. When compared to the discharge rate data of November, 1999, it is noted that there is a distinct rise in discharge rate of some tributaries within

Table 14. Discharge rate in the Maw-ki Syiem creek and in its tributaries during November 1999–2001 (localities indicated on Fig. 16)

Locality (*tributary)	Discharges (ls^{-1})		
	20 Nov. 1999	12 Nov. 2000	24 Nov. 2001
Q1	2.76	2.30	1.38
Q2*	0.06	0.01	.
Q3	2.51	1.77	1.31
Q4*	0.08	0.12	.
Q5*	0.29	0.404	0.245
Q6*	0.092	0.077	.
Q7	.	0.99	.
Q8	.	0.46	.
Q9	0.147	0.31	.
Q10	0.175	.	.
Q11	0.45	0.50	0.39
Q12/13	1.39	1.63	.

the catchment in November, 2000 (Q4, 5, 9). On the other hand, someof the smallest tributaries record a decline (Q2 and 6) during the same time (Table 14). In November, 2001, there is a general drop in discharge, when the measurements were taken much later (24 November).

Comparing such data of discharge rate with the rainfall totals (Table 15), it is found that there is a rising trend in rainfall in the consecutive years (1,030 mm from 1st September, in 1999 and 1,822 mm in 2001). The total rainfall precipitated starting from the month of October shows a fluctuating trend in creek discharge.

Table 15. Excessive rainfall (mm) preceeding discharge rate measured in the Maw-ki Syiem catchment

	20 Nov.1999	12 Nov.2000	24 Nov.2001
from 1 September	1030	1315	1822
from 1 October	628	275	555
last extreme rains (days before)	32 days 342 mm (in 3 days)	15 days 208 mm (in 3 days)	24 days 82 mm (in 2 days)

Contrary to it, there appears to be a distinct coincidence with time of last preceding heavy rains and its totals. The highest discharge rate was recorded in most of the localities (Q 4, 5, 9 and 11) during the month of November, 2000, when last preceding 2-days rainfall of 208 mm took place only 15 days before the records were taken (in 1999 up to 32 days earlier). However, the lowest discharge rate was recorded in 2001 when preceeding rainfall was only 82 mm. It occurred 24 days before the measurement (earlier heavy rains were recorded in early October).

All such data point to the storage of groundwater during heavy rains and gradual draining out of the water from the reservoirs during dry winter season. Probably, the maximum of rainwater is stored in the upper part of the catchment, where many quarries and pits connected with the coal mining activities exist. Therefore, water is flowing throughout the whole of the dry winter in the main creek and main springs and continuous outflow of around 0.01 $m^3km^{-2}s^{-1}$ is measured at the mouth of the catchment. Last records taken in February, 2003 showed that the discharge decreased by 70 to 80% during the three dry months.

Sporadic measurements of the water level were carried out at the outlet of Maw-ki Syiem creek on the bridge by local teacher Mrs. C. Swett during the rainy season of 2002. These measurements delivered important information pertaining to rapid water level which rose during continuous rains and their sudden rapid drops (Photo 12). Very low water level (similar to these in November) was noticed during the reconnaissance exercise undertaken in July, 2001 and 2002.

We considered the month of June, 2002 for detailed analysis, when Cherrapunji received 3,229 mm of rain of which nearly two-thirds was precipitated in 8 days between 12th and 19th June, 2002 (Table 16, cf. Fig. 22). The highest daily rain exceeded 500 mm on 13th June of the same year; the intensities per hour in two days exceeding 60 mm (1 mm min^{-1}). As many as 10 measurements of water level were taken between 10th June and 2nd July 2002. Before the continuous rains on 10th June, water level reached up to a height of 0.1 m and, then on 14th June morning, it passed 1.5 m mark. But the observer registered fresh sand and gravels deposits on higher elevation indicating a level several tens cm higher.

During the 8-day rainstorm (12th to 19th June, 2002), the water level was recorded 3 to 4 times higher. But on 26th June, 2002, it is recorded 2 m with a fast increasing trend. It passed over the maximum level of the measurement and was flowing over the bridge for a few hours. Surprisingly, the Cherrapunji meteorological station registered much less rain on that day (<50 mm). It means that there would be a local storm with very high rainfall intensity for few hours in the catchment. It is difficult to calculate the discharge at the creek. But if we calculate the mean velocity of water in the creek (of order 3 m^3s^{-1}), then the discharge should be in the order of 20 to 25 m^3s^{-1} and the unit runoff may reach 100 $m^3km^{-2}s^{-1}$ when the water level is more than 2 m high.

High to very high fluctuations of discharge and water level obviously indicate a low rate of infiltration and less water holding capacity of the soils. The saturated impermeable stratum is, thus, responsible for rapid overland flow. However, it may be assumed that the coal field pits and several gullies absorb substantive rainwater and increase the infiltration rate to stabilise the discharge rate at the outlet of the catchment.

Table 16. Daily rainfall (mm) and water level (m) in Maw-ki Syiem during June 2002

Day	Rainfall	Water level	Day	Rainfall	Water level
1	4.7		16	256.1	
2	1.3		17	230.6	1.5
3	23.8		18	390.4	
4	17.2		19	183.7	1.0
5	109.2		20	58.7	
6	30.3		21	15.5	1.5
7	18.6		22	61.9	
8	10.9		23	38.8	
9	24.8		24	27.3	
10	98.0	0.1	25	20.3	
11	47.0		26	49.8	2.0
12	161.8	0.3	27	79.1	
13	505.0	0.5	28	111.3	
14	238.3	1.5	29	216.7	
15	117.2		30	80.5	1.5

10. RAIN AND STREAM WATER CONDUCTIVITY AND PH

Roman Soja

The conductivity of flowing water is an indirect indicator of chemical denudation. Measurements of pH and conductivity of rain and stream water were carried out during the summer monsoon season. The „acid rains" with pH below 5.6 were measured during three consecutive summers in Cherrapunji. The origin of acid rains just in Cherrapunji is difficult to explain and further studies are needed.

The total rainfall from 2 to 4 July 2002 was greater then 320 mm, and the pH of rain water fluctuated between 5.40 and 3.30. Rainfall rates greater than 50 mm were observed only at night. The lowest pH values occured were connected with weak rains during the day. Measurements from summer 2001 are similar.

The conductivity of rain water fluctuates between 5.7 and 32.3 $\mu S\ cm^{-1}$. Rainfalls with low and extremely low conductivity dominate. Very high values are rare, but in mid-July, 2002 rainfalls with conductivity greater than 100 μS were recorded. These high values were associated with the appearance of yellow, mineral dust, which was deposited on the bottom of the rainfall collector. Similar events during previous summers were not observed.

Conductivity fluctuates with rainfall intensity. High hourly intensities are related to low conductivity and low intensities to high conductivity. During continuous rains short 1–2 hour long periods were recorded, with rapid fluctuations in conductivity and less distinct variations of pH.

The streamwater displayed showing high differentation of pH and conductivity. In July 2002 the pH of streamwaters in the Maw-ki Syiem experimental catchment in July, 2002 varied from 4.80 to 6.00 and conductivity varied from 30 to 50 μS. The large spatial differentation in water conductivity is related to the various water source supply. Water flowing from small swamps and periodic springs had conductivities of 60–80 μS. Water from larger streams of 10 km^2 catchment that drained the limestone areas had much higher conductivities of 150–200 μS. Main rivers flowing in the canyons with discharges of 20–30 m^3s^{-1}, and draining areas of crystaline rocks had pH values around 6.0 and conductivities around 80 μS.

On the plain of low pH and low conductivity of streams draining the sandstone surface of Cherrapunji Spur very distinctly differ rivers of southern margin fed by deep groundwaters from limestone and metamorphic rocks. There exists a large system of caves filled with water during the rainy season. For instance, streams surrounding of Laitkynsew on the SW slope of Cherrapunji spur had pH values upto 7.0 and conductivities 250–450 μS.

The chemical denudation in the area of Cherrapunji is a dominant process, but differentiated in space. Streams draining limestone had conductivities 3.5 times higher then those draining the sandstone plateau or the metamorphic rocks.

11. SOIL EROSION IN EXPERIMENTAL CATCHMENT

Wojciech Froehlich

11.1. INTRODUCTION

Extreme rainfall in Cherrapunji region creates potential conditions for efficient soil erosion. The high energy of events introduces important technical constraints in the application of traditional and classical techniques in investigation of soil erosion. Studies in many areas of the world have demonstrated that ^{137}Cs technique provides a valuable tool to estimate medium-term (ca. 45 years) rate of soil loss (e.g. Loughran 1989; Martz, De Jong 1991; Walling, Quine 1990; Froehlich et. al. 1993; Froehlich, Walling 1997; Walling, He 1999; Walling, Collins 2000).

^{137}Cs is an artificial radionuclide with a half-life of 30.17 years which was released into the environment as a result of atmospheric testing of thermonuclear weapons, primarily during the period from 1954 to the mid-1970s and also as a consequence of Chernobyl nuclear power plant accident in 1986. Most of the fallout occurred in the decade between 1956 and 1965 with maximum deposition in 1963 which was the year of the Nuclear Test Ban Treaty. The ^{137}Cs was distributed globally within the stratosphere and deposited as fallout, mostly in association with precipitation. At present, more than 50% of the original fallout would still remain in undisturbed sites.

The ^{137}Cs became adsorbed to the surface soils and could be used as a tracer of soil down slope movement. Most studies indicate that ^{137}Cs does not move in solution under most soil conditions. Strong adsorption is evidenced by the low rate of vertical migration of ^{137}Cs, evident for many soil types in both field and laboratory experiments (cf. Tamura 1964; Squire, Middleton 1966; Bachhuber et al. 1982; Frissel, Pennders 1983; Cremers et al. 1988). The empirical and experimental evidences indicate that subsequent redistribution of the ^{137}Cs takes place in association with the erosion, transport and deposition of soil particles by both water and wind (Rogowski, Tamura 1965, 1970). A.S. Rogowski and T. Tamura (1970) observed that about 90 % of the loss of ^{137}Cs from a bare Captina soil plot in Tennessee, USA, could be attributed to soil erosion.

It is generally assumed that the total ^{137}Cs fallout can be treated as homogeneous at the scale of the field or small basin (cf. Walling, Quine 1990; Walling, Collins 2000). ^{137}Cs technique was used for the study of soil loss in the small Maw-ki Syiem catchment covering an area of ca. 22 ha. There was a lack of experience to use this method in the areas of extreme rainfall like Cherrapunji where large intensity of the saturated overland flow is noticed. Usually, this type of flow generates higher rates of soil erosion and greater transport distances of soil particles than discontinuous overland flow.

11.2. METHODS OF INVESTIGATIONS

Soil samples were collected in November 1999 and 2000. Due to paucity of available time in the field, sampling strategies in the Maw-ki Syiem catchment were based on a transect approach to determine soil erosion on slopes. The sampling network comprised of two down slope transects with 12 sampling points. The sampling sites were located with a spacing of 5 to 8 m between sampling points. Reference sites for ^{137}Cs were sampled on top of grass hillcrests. The grass cover was similar at each of the sites. In addition, five samples of foot slope waste cover and overbank deposits were collected in the downstream part of the catchment. The total number of cores analysed was 21.

Soil cores were obtained by hammering a 75 mm diameter steel corer into the ground. Because of very hard skeletal fractions, pavement up to 20 cm below the soil surface and relatively small amount of fine fraction cores was sectioned at 3 cm intervals prior to analysis. However, sectioned at 2 cm intervals, the profiles were obtained from five potential depositional sites at the base of the slope and three others from over bank deposits at the outlet of the catchment. The samples were collected at sufficient depth in order to include all ^{137}Cs present in the soil and colluvial/alluvial deposits profile.

Soil samples were dried at 90°C for 48 hours weighted and were passed through a 2 mm screen. Skeletal fractions greater than 2 mm were discarded. The 100 g of <2 mm fraction were packed into 500 dm^3 Marinelli beakers for gamma-ray analyses. The analysis was made at the Homerka Laboratory of Fluvial Processes, Institute of Geography and Spatial Organization, Polish Academy of Sciences at Frycowa using the PerkinElmer (EG&G ORTEC) Digital Gamma Ray Spectrometer (DSP^{EC}) working in 16,384 regime channel spectra with High-Purity Germanium coaxial detector (45% efficiency and 1.4 keV resolution).

The system was calibrated with Standard Reference Materials and the International Atomic Energy Agency Standard IAEA-6 Soil and IAEA-327 Soil. Estimates of the ^{137}Cs activity of the soil samples were made using the PerkinElmer Instruments GammaVision A66-B32, version 5.13 software. 137Cs was detected at the 661.62 keV photopeak and count time for each sample was 24 hours, providing a measurement precision of ±4 to 6%. Sub-samples of each of the cores collected at each sampling point were combined and analysed for particle size characteristics using a Malverm Master Sizer S, after pre-treatment with H^2O^2 and dis-aggregation, and for organic matter content by loss-on-ignition at 600°C for three hours.

The use of ^{137}Cs to estimate soil erosion and deposition rates is based on a comparison of ^{137}Cs activity at a sample site with concentration of ^{137}Cs measured at the reference site (input site). Sample sites with ^{137}Cs concentrations, less than the reference sites, are the sites of erosion while sample sites with concentrations greater than the reference sites are the sites of deposition. In relation to uneroded reference site, the net erosion and deposition of ^{137}Cs at a soil sampling site can be expressed as a percentage of the reference value. The accuracy of erosion rate estimates depend on the reliability of the calibration relationship employed.

Calculations of erosion and deposition rates based on ^{137}Cs activity are made, using the models and software developed by Walling and He (1997, 1999). However, the technique requires a number of assumptions about the environmental behaviour of ^{137}Cs, and the relationships between ^{137}Cs loss and soil erosion (e.g. Walling, Quine 1990; Loughran et al. 1990; Ritchie, McHenry 1990; Walling, Collins 2000).

11.3. THE RESULTS

The depth distribution of ^{137}Cs activity in the five referenced sites was examined in order to provide background information on the behaviour of the fallout of ^{137}Cs within the soil in the Maw-ki Syiem catchment to assist with the interpretation of the ^{137}Cs inventories. Precise estimation of the reference value is fundamental for calculating losses and gains of ^{137}Cs to determine erosion and deposition rates. However, we do not know the site history and its stability but the referenced sites were situated in direct neighbourhood of transects on 1,355 to 1,367 m a.s.l. It has been possible to consider that they have a similar history of precipitation and fallout ^{137}Cs. The ^{137}Cs inventory at these locations, therefore, represents the accumulated atmospheric input per unit surface area, adjusted for radioactive decay. Although the local rain and fallout of ^{137}Cs pattern may not be spatially uniform for individual events, the deposition by numerous events over an extended period probably minimizes the local variation (e.g. Walling, Quine 1990). In this context, the question arises as to how rain influences the large intensity of overland flow generated in its extreme conditions for adsorption of ^{137}Cs by the clay particles down slope.

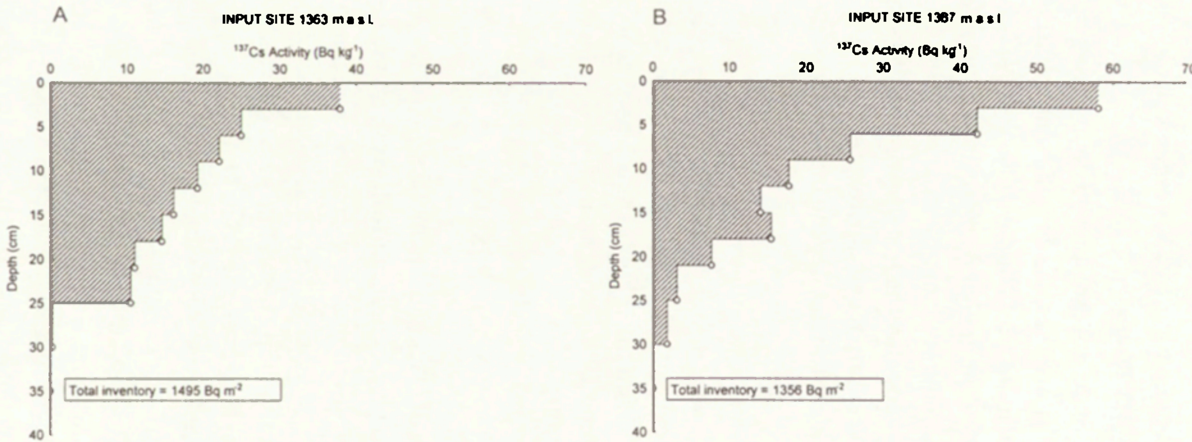


Fig. 28. Distribution of ^{137}Cs in the soil profiles collected from reference sites (by W. Froehlich)
A – reference soil profile, B – average distribution of 12 soil profiles

Rozkład koncentracji ^{137}Cs w profilach glebowych na stanowiskach reperowych (oprac. W. Froehlich)
A – profil reperowy, B – średni rozkład z 12 profilów glebowych

The ^{137}Cs inventory was measured for each sample to provide a series of point inventories for the study area. Figure 28 shows typical depth distributions of ^{137}Cs in referenced soil profiles, which is typical of an undisturbed soil profile with highest concentration in the surface soil layer (cf. Walling, Quine 1990; Walling, Collins 2000). Below the peak activity of concentration at about 2 to 3 cm, the profile shows an exponential decline in ^{137}Cs activity with depth. In each case, more than 80% of the total inventory occurs in the top 15 cm, indicating that downward transfer is minimal. Much of the vertical translocation of ^{137}Cs in these profiles can be related to organic matter production at the surface and bioturbation as well as chemical diffusion and also downward transport by macropores. Analysis of the referenced samples provided an estimate of the reference inventory for the catchment of 1,425 Bq m^{-2}. Amounts of fallout generally increase with increasing rainfall (e.g. Longmore 1982; Cawse 1983; Cawse, Horril 1986). Further sampling is required to investigate both the local and regional variability of fallout input in the Meghalaya Plateau as a whole and to assess its influence on the error of erosion estimates.

The distribution of ^{137}Cs of two downslope transects, in general, is typical of eroded undisturbed soil. The average ^{137}Cs distribution of 12 soil profiles shows inventories decreasing with depth (Fig. 29). Erosion rates for the slopes in the Maw-ki Syiem catchment were estimated using a calibration procedure described by Walling and Quine (1993). The profile simulation model of soil and ^{137}Cs redistribution was adapted to account for ^{137}Cs diffusion after initial fallout receipt.

As a general indication, inventories in excess of 1,600 Bq m^{-2} may be identified with soil deposition and those lower than 1,250 Bq m^{-2} indicate areas of soil loss (Fig. 29). For integrated data along the transects, the estimated soil loss rate is 0.21 kg m^{2} yr^{-1}. The distribution of ^{137}Cs inventories on the steep slopes covered by local grass are the evidences of minimal soil redistribution. However, the absence of consistent relationships between erosion rates and topographic parameters for Cherrapunji region which are commonly used in calibration of erosion estimation procedures raises important questions concerning the accuracy of soil erosion rate.

The soils are heavily degraded and quite often devoid of upper horizons and they, in many places, have a character of waste cover only. Probably the previously forest cover protected the soil much more effectively before degradation of heavy rainfalls. The clearances of forests, shifting cultivation and expanding grassy communities cause the changes occurring in the previous forest – slope – soil catena. The cultivation practices, overgrazing and simultaneous-

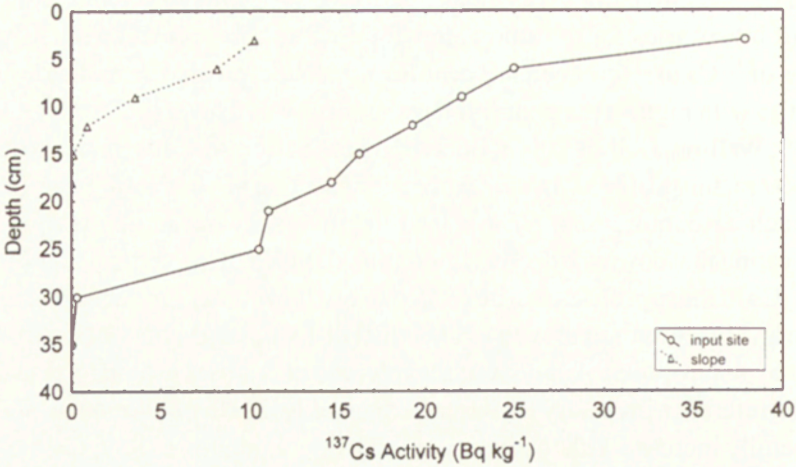


Fig. 29. Concentration of ^{137}Cs at the input site and on the slope (by W. Froehlich)
Koncentracja ^{137}Cs na stanowisku reperowym i na stoku (oprac. W. Froehlich)

ly effective raindrop have direct impact on the overland flow. At the time of the excessive overland flow, it accelerates soil erosion which is the cause of substantial degradation of upper soil. These processes fast remove fine sediment and produce armoring debris and very hard impermeable layers on soil surface which range up to 30 cm. In some places of slopes, the bedrock is exposed which is an effect of very intensive soil erosion experienced in the past.

The magnitude of radiocaesium transfer from the slopes to valley bottom and its vertical distribution in footslope profiles suggest an accumulation rate about 1.5 mm yr^{-1}. Dense grass covering footslope and valley bottom is acting as a filter to retain eroding soil particles in the upper slopes.

11.4. CONCLUSION

Indirect assessment of surface erosion using the radionuclide tracer ^{137}Cs has been used to estimate medium term soil erosion rate at the Maw-ki Syiem catchment. The study of soil erosion and sediment transfer in this area creates the exceptional opportunity to determine the role of large frequency inter-arrival time of extreme rainfall on sediment production and mobilisation as indicators of relaxation of the fluvial system. These studies serve as a preliminary investigation to assess the possibilities of employment of the ^{137}Cs technique for determining the rate of soil erosion in an area of extreme rainfall.

The spatial distribution of ^{137}Cs inventories in the Maw-ki Syiem catchment clearly reflects the present day erosion-deposition pattern. The ^{137}Cs inventories are considerably lower at the slopes than at the ridges of watershed and they are highest at the footslope and valley floor. The differences indicate erosion on the slopes and deposition in the valley. Use of ^{137}Cs has contributed significantly to understand rates of surface erosion in Cherrapunji spur. Preliminary observations reveal that the very small amount of soil is eroded within the slopes which are covered by grasses and such eroded material is deposited at the foot of the slopes. From the ^{137}Cs data, it is shown that the compact pavement surface of the soil has exerted greater control over the export of sediment from the steep slopes rather than energy impact of the extreme rainfall.

Magnitude of ^{137}Cs transfer from slopes to the valley bottom and its vertical distribution on the foot of the slope profiles suggests a deposition rate of about 1.5 mm yr^{-1}. The lack of evidence for contemporary ^{137}Cs deposition on the slope longitudinal profile suggests that sediment delivery ratio is very low for the slope surface. The erosion is very high only in several active gullies at the headwater part.

This indicates that present day sediment delivery ratio is low for grassy slopes but relatively high for active gullies during extreme events only. When the recurrence intervals for extreme events are very short, then the relaxation time is not sufficient to sediment production and mobilization. Low rate of soil erosion and acceleration of sediment routing is a present day characteristic feature of the Cherrapunji region.

The study has shown that present day rate of soil redistribution by surface erosion processes is very small. However, its intensity is altered by the intensification of human interventions, deforestation, grass and forest fires, overgrazing and poor farming practices on the steep slopes especially during the last 50 years. In view of their great impact on sustainable agricultural production and environmental conservation, there is an urgent need to assemble quantitative data on the extent, magnitude and present rates of soil erosion as well on their economic and environmental consequences. Further work, using the potential of ^{210}Pb, ^{226}Ra, ^{241}Am and ^{137}Cs methods, may be planned in future in order to develop an understanding of sediment transfer within this area of the extreme rainfall.

12. CONCLUSIONS AND DISCUSSION

Wojciech Froehlich, Pawel Prokop, Surendra Singh, Roman Soja, Leszek Starkel, Hiambok J. Syiemlieh

12.1. SPECIFIC FEATURES OF CHERRAPUNJI AREA

The specific features of this area have been identified as the geological as well as the geomorphic conditions, monsoonal rainfall regime with the highest rainfall in the global scale and deforestation combined with overexploitation of various natural resources.

The southern part of the Cherrapunji spur is built mainly of horizontally bedded sandstones (in the south also limestones) which control the direction of runoff and soil erosion reaching up to resistant beds. The young uplift along the system of faults created high tectonic escarpment dissected by deep canyons (Photo 1).

The marginal areas of the plateau are receiving the highest rainfall on a global scale, fluctuating between 7,000 mm and 24,000 mm annually. About 90% of the rain is concentrated only in 4 to 5 months during the rainy season. In winter 3 to 4 months, this area does not record any significant rainfall. It is observed that the extent of clustering of rain in summer is such that over 2,000 mm rain is received in a single week. This distinct monsoonal seasonality is clearly expressed in water circulation, soil erosion and biomass production.

Deforestation and shifting cultivation in the past are other specific features of the Cherrapunji spur which cause accelerated runoff resulting in soil degradation and transformation of former tropical forest into grassland (Ramakrishnan 2001). These grasslands suffer further due to overgrazing and practices of fire. However, degradation of the surface of the plateau is also due to overexploitation of mineral resources, mainly of coal and sandstone in the northern and central part and limestone in the south of the spur.

12.2. LONG-TERM TRENDS OF LANDSCAPE EVOLUTION

The natural evolution of landscape started with the development of hilly surface of the plateau with deep lateritic weathering during the Neogene and Quaternary periods. Formation of the high escarpments, which still continues

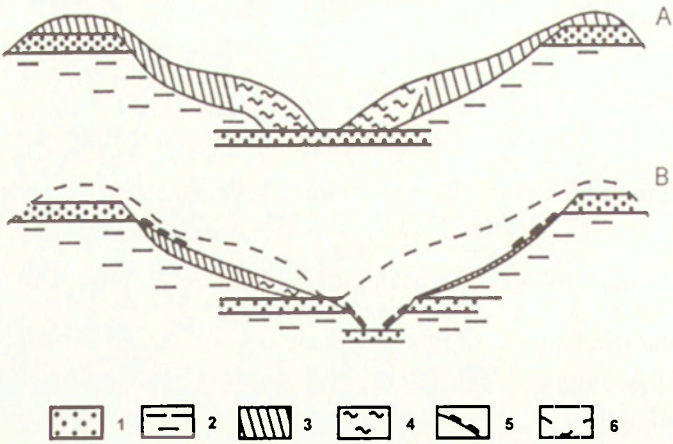


Fig. 30. Model of evolution of small valley over the Cherrapunji spur (similar to Mawki Syiem creek, by L. Starkel)
A – before deforestation, B – present-day situation. 1 – resistant sandstone beds, 2 – less resistant sandstones and shales, 3 – regolith of laterithic type, 4 – colluvial deposits (also deeply weathered), 5 – sliding sandstone blocks, 6 – former valley transect
Model ewolucji małej doliny na Płaskowyżu Cherrapunji (podobnej do potoku Maw-ki Syiem, oprac. L. Starkel)
A – przed wylesieniem, B – stan dzisiejszy. 1 – odporne ławice piaskowca, 2 – mniej odporne piaskowce i łupki, 3 – zwietrzelina typu laterytowego, 4 – osady koluwialne (także głęboko zwietrzałe), 5 – zsuwające się bloki piaskowcowe, 6 – przekrój doliny z poprzedniego okresu

to rise along the fault-lines, was followed by the dissection of tectonic scarp by falling waters of rivers flowing over the plateau. Retreating of waterfalls is responsible for the formation of deep canyons. Incision gradually follows upstream, rejuvenating the flat valley floors and is marked by small falls and rapids, exposing the bedrocks in the river channels. Presence of resistant beds created very characteristic step-like topography of ridges and slopes with retreating escarpments as well as flat valley floors (Fig. 11, 30). The retreating slopes begin to be stabilised by blocks sliding from the more resistant beds.

Progressing deforestation combined with practices of shifting cultivation in the past centuries as well as removal of the soil during exploitation of mineral resources, especially coal and loams applied in cement production, has caused the exposure of the surface to direct rain activity, to overland flow and slope wash. As a result, only a small part of the former lateritic regolith and colluvial deposits have still been preserved (Fig. 30), facilitating deepening of the valley floors.

Expansion of grassland formation accompanied by overgrazing and fires has caused the formation on the degraded surface either as an armoured layer pavement built of coarse rock fragments and iron concretions or even the exposure of hard bedrock.

12.3. PRESENT-DAY PROCESSES

The climatic regime of extreme rainy region of the world controls the seasonality of physical and chemical processes. There are three distinct seasons: dry winter, spring with rare heavy rains and the 4 to 5 months long summer rainy season with frequent continuous rains and downpours. The daily rainfall exceeds every year 500 to 700 mm. In the last decades, we observe a distinct increase of daily rainfall-totals (chapter 7).

Deep degradation of the soil and lack of dense vegetation cover facilitate an overland flow partly directed by axes of gullies and paths. The resistant surficial layer armoured in coarse gravels or the exposed bedrock with iron crust reduces the infiltration rate to at least 20 to 30 mm $hour^{-1}$. In conditions of frequent high rainfall intensities, the start of the Hortonian saturated overland flow is passing practically during every rainy day. There are instances of such events during 10 consecutive rainy days in June 2002 where probably, most of the infiltration rates have been overtaken during 30 hours of rain (Fig. 22). Only part of that water may be seasonally stored in the grassland at the foot of the slopes, but most of it flows down to the rocky channels. Therefore, it has resulted into the rapid rise and rapid fall of the water level in the channels. The proportion of rainy water stored underground is still unknown, but from several measurements in the Maw-ki Syiem creek, it is known that the discharge is continuously decreasing during the dry season in autumn after the last heavy rains came down to the order of 0.01 $m^3\ km^{-2}s^{-1}$. The preliminary estimation shows that the discharge during the flood is in the order of 100 $m^3\ km^{-2}s^{-1}$, reaching one of the highest values in the global scale (cf. Todd 1970).

The study of soil erosion and sediment transfers in this area is an exceptional opportunity to understand the role of large frequency inter-arrival time of extreme rainfalls in the sediment production and mobilisation as indicators of the relaxation time of the fluvial system. The preliminary result suggests that a very small amount of soil is eroded within the grassed covered slopes and is deposited at the foot of the slopes. Lack of evidence for contemporary ^{137}Cs deposition on the slope longitudinal profile indicate that sediment delivery ratios are very low for the slope surface but probably high in active gullies at the headwater part. The magnitude of $^{3'}Cs$ transfer from the slopes to the valley bottom and its vertical distribution in the foot slope profiles suggest a deposition rate about 1.5 mm yr^{-1}. Dense grass covered foot slope and valley bottom act as a filter to retain eroded soil particles.

The ^{137}Cs data suggest that, at the slopes, the compact pavement surface of soil has exerted a greater control over the export of sediment from the steep slopes than the energy impact of the extreme rainfalls. This indicates that present day sediment delivery ratios are low for grass covered slopes. The recurrence intervals for extreme events are very short. Therefore, the relaxation time is not sufficient for sediment production and mobilization. Low rate of soil erosion and accelerated sediment routing is the present day characteristic feature of the Cherrapunji region.

Only in areas dissected by young gullies and exposed surfaces after exploitation of coal, clay, or weathered sandstone, the sediment load is much higher and during high intensity rain even gravel fractions are removed and deposited temporarily at the base of the slopes or on the flat segments of valley floors.

The rate of chemical denudation in the sandstone zone is relatively low in relation to limestone areas. Several occasional measures indicate that the dissolved load is of the order 200 t $km^{-2}yr^{-1}$.

In the river channels, mainly cut in bedrock, the bed load is restricted to the steeper gradients. Due to the formation of iron crusts on the rocky channel floors during the dry season, we observe that the lateral expansion of channel is disproportionately wide in relation to their discharges during the heavy rains. The undermining of river banks leads finally to the embankment of channels by sliding blocks. The regressive erosion is more extensive in the valley heads of deep canyons where the rock-falls and slumps following the systems of joints combine their effects with the waterfalls.

The dry season is the period of much reduced activity. But on the exposed surface the evaporation of water causes the concentration of iron and manganese on the surface and formation of iron crusts, typical of desert zones.

Probably the previous forest cover protected the soil much more effectively against degradation. The cultivation practice, overgrazing and exploitation of mineral resources have had a cumulative effect on the area, combined with raindrop impact and overland flow produced by heavy rainfalls to accelerate soil erosion. These processes caused the removal of fine sediments, producing the armoured debris and a very hard impermeable layer on soil surface. In many places, the soils have a character of waste cover only.

The extensive land use in the conditions of extreme monsoonal rains caused the establishment of new „sterile" and stable system with high overland flow, minimal loss of matter and very low production of biomass (cf. Starkel et al. 2002).

This system is self organised. It includes elements of the processes characteristically belonging to the monsoonal climate as well as desert environment. Their coexistence came to being, thanks to the extensive and varied human activities as well as to the specific lithological and geomorphic conditions. It is still an open question when this new „sterile" system has come into being. May be, it is the effect of several centuries or only last two centuries, as may be suggested by the abandoned cultivation practices around Cherrapunji.

12.4. POSSIBILITIES OF RECOVERY OF NATURAL RESOURCES

The question of re-naturalisation of degraded geo-ecosystems has been raised a long time ago by many natural scientists (Messerli, Ives 1989; Ramakrisnan 2001). In case of substantially changed systems which reached the „sterile" stage, every activity to restore the water resources, soils and finally vegetation cover should be done very carefully, at first on small experimental plots and catchments.

The recovery of water resources, basic element for every living organism as well for all branches of economy and so important for the prosperity of population should be concentrated on increasing the water storage component and on reducing the runoff. The groundwater storage may be done by the increase of infiltration with the help of re-vegetation and formation of new active soil horizon. The surfacial storage can be increased by construction of hundreds of small dams and barrages which may also be used as fish ponds. At the same time very strong rules should be introduced against water pollution, starting from headwater springs.

Re-vegetation should be taken up step by step. In so deeply degraded environment the direct introduction of native species of trees and shrubs may be restricted to small areas. It would be more profitable to start with the introduction of new grasses and trees which can accept the desert-like conditions of dry season. The physical properties and water circulation conditions of upper soil horizons and practically deficiency of fine material and nutrients will be the main causes of difficulties in re-afforestation of this area. At the beginning of such initiatives, restrictions of such practices like cutting of trees, fires and overgrazing in the grassland should be imposed. The experiments carried by CAZRI, in Jodhpur in Rajhastan have shown that by elimination of overgrazing through several years, we may get the open savannah instead of semi-desert.

The most difficult aspect is the restoration of soil in the condition of the removal of A horizon and developed resistant blanket on its surface (Photo 10, 11). The surficial exploitation of coal and loamy cover facilitating the washing down of remained soil to the depressions should be forbidden and only re-vegetation can give positive results in the long run. At the local scale, the crushing and removal of armoured surficial horizon may give positive results especially on the gentle slopes during afforestation.

In order to answer all these questions related to the restoration of productivity of this most humid geo-ecosystem, there is an urgent need to establish very intimate cooperation with ecologists, agriculturists and foresters. From our side, collection of more precise quantitative data on the extent, magnitude and present rates of runoff and soil erosion as well on their economic and environmental consequences would be required. Further studies are required in order to obtain a clear appreciation and understanding of the mechanisms of processes of this area and of the role of anthropogenic forces in integrating the landscape characteristics and its re-naturalisation.

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OPAD, SPŁYW WODY I EROZJA GLEB W EKSTREMALNIE WILGOTNYM KLIMACIE W REJONIE CHERRAPUNJI, INDIE

Streszczenie

1. WPROWADZENIE

Monografia jest efektem współpracy zespołu Zakładu Geomorfologii i Hydrologii Gór i Wyżyn Instytutu Geografii i Przestrzennego Zagospodarowania PAN w Krakowie z Instytutem Geografii North Eastern Hill University w Shillongu zainicjowanych wizytą polskiego zespołu w 1996 roku w ramach wymiany PAN–INSA. Później temat spływu i erozji gleb został włączony do międzynarodowego programu współpracy Komitetu Badań Naukowych i Department of Science and Technology rządu indyjskiego (w latach 2000–2002). W pierwszej fazie badań skoncentrowano się na następujących zagadnieniach: charakterystyka opadów i warunki obiegu wody, fizyczne i hydrologiczne właściwości gleb na tle rzeźby i budowy, ocena intensywności spływu wody i denudacji, przyczyny powstania zdegradowanych geoekosystemów i możliwość odnowy zasobów wodnych, glebowych i roślinnych.

Ekstremalne opady rejonu Cherrapunji stwarzają specyficzne warunki rozwoju krajobrazu. Wpływa na to położenie na krawędzi wysoko wyniesionej Wyżyny Meghalaya i specyficzna budowa geologiczna. Istotnym czynnikiem jest sezonowy rozkład opadu charakterystyczny dla klimatu monsunowego. W wyniku wylesienia i uprawy roli doszło do przyspieszenia w obiegu wody i substancji mineralnych co łącznie z eksploatacją surowców doprowadziło do degradacji zasobów naturalnych.

Monografia obejmuje charakterystykę środowiska od skali przeglądowej do szczegółowej, analizę procesów od opadów poprzez obieg wody do erozji gleb oraz podsumowanie uwypuklające przyczyny i skutki procesów przyspieszonego obiegu materii.

2. PRZEGLĄD LITERATURY

Środowisko przyrodnicze Płaskowyżu Cherrapunji było opisywane już od polowy XIX wieku. Zwracano uwagę zarówno na wysokie opady (Mills 1853), cechy budowy geologicznej (Oldham 1854) jak i na skalę wylesienia (m.in. Chatterjee 1968; Bandyopadhay 1972; Starkel 1972; Mazumdar 1976). W latach 1980-tych podjęto szczegółowe badania nad degradacją ekosystemów i rolą gospodarki rolnej w powstaniu wtórnych zbiorowisk trawiastych (Toky, Ramakrishnan 1981, 1982; Ramakrishnan 2001). Zasługują na podkreślenie prace z zakresu hydrologii oparte o leżącą na północnym skłonie wyżyny stację w Barapani (Sathapathy 1995–1996). Prace z zakresu klimatologii są również nieliczne oparte o dane ze stacji meteorologicznej w Cherrapunji. Z przeglądu literatury wynika dotkliwy brak studiów nad obiegiem wody w obszarze o rekordowo wysokich opadach w rejonie Cherrapunji.

3. MATERIAŁY, METODY I TECHNIKI

Opracowanie zostało oparte o 3 rodzaje źródeł: dane publikowane, kartowanie terenowe i analizy laboratoryjne oraz monitoring procesów. Dane publikowane i archiwalne obejmują mapy topograficzne 1:50 000, mapy geologiczne, zdjęcie satelitarne (dla rekonstrukcji szaty roślinnej i użytkowania ziemi) i dane statystyczne o gospodarce i ludności. Osobną grupę stanowią dane opadowe dla Cherrapunji, miesięczne (1902–2000), dobowe (1986–2000) i pluwiograficzne, a także dane z posterunku opadowego w Mawsynram.

Badania terenowe objęły kartowanie geomorfologiczne, analizy składu mechanicznego, przepuszczalności i pojemności wodnej gleb oraz badania laboratoryjne zawartości izotopów radioaktywnych ^{210}Pb, ^{226}Ra, ^{241}Am i ^{137}Cs w celu określenia skali erozji gleb i sedymentacji.

Monitoring koncentrował się na badaniach natężenia opadów i ich rozkładu przestrzennego przy pomocy 2 pluwiometrów SEBA zainstalowanych w dwu ostatnich latach.

Obok tego okresowo dokonywano pomiarów przepływu i stanów wody w małej zlewni eksperymentalnej Maw-Ki-Syiem, a także sporadycznie pomiarów przewodnictwa właściwego wody i denudacji chemicznej.

4. ŚRODOWISKO PRZYRODNICZE WYŻYNY MEGHALAYA

Wyżyna Meghalaya jest asymetrycznym zrębem tektonicznym oddzielonym na północy od Himalajów doliną Bramaputry i uskokiem Dauki od Niziny Bengalskiej na południu. Trzon wyżyny, wznoszący się do 1800–2000 m n.p.m., budują prekambryjskie kwarcyty i gnejsy w które wdarły się intruzje granitowe formując rozległe batolity. Południowa krawędź wyżyny przykryta jest zalegającymi niemal poziomo piaskowcami i mułowcami z wkładkami węgla oraz wapieniami wieku kredowo-paleogeńskiego o miąższości kilkuset metrów.

Pierwsze ruchy podnoszące datowane na okres jury zaznaczyły się wylewami trapów bazaltowych, których odsłonięcia widoczne są na południowej, stromej ścianie wyżyny. Od tego czasu obszar ten jest stale aktywny tektonicznie co przejawia się w licznych trzęsieniach ziemi, a obecność wielu wodospadów wskazuje na odmłodzenie rzeźby. Litologiczne kontrasty oraz aktywność tektoniczna wpływają na energię rzeźby i kształt dolin rzecznych. W centralnej części wyżyny dominuje dojrzała rzeźba z zaokrąglonymi pagórkami i płytkimi, dolinami. Południowa krawędź, znajdująca się w strefie ekstremalnych opadów, rozcięta jest głębokimi na 500–1000 m kanionami rzek.

Głównym typem pokrycia terenu na Wyżynie Meghalaya są naturalne, wiecznie zielone lasy tropikalne i subtropikalne. Pozostałe formacje – lasy sosnowe, bambusowe i trawy stanowią roślinność wtórną, rozwiniętą na obszarze wcześniej zdegradowanym. Naturalne lasy zachowały się głównie w głębokich kanionach. W piętrze od 1300–2000 m n.p.m., gdzie dominują trawy i lasy sosnowe, rozwinęło się rolnictwo, które stanowi podstawę utrzymania miejscowej ludności. W obrębie den dolin przeważa uprawa ryżu, na krótkich i stromych stokach od XIX wieku rozwinęła się uprawa ziemniaka. Stosunkowo rzadko spotykany jest terasowy system uprawy, stąd nawet niewielkie poletka narażone są na procesy intensywnej erozji wodnej.

5. ŚRODOWISKO PŁASKOWYŻU CHERRAPUNJI

Płaskowyż Cherrapunji jest odizolowanym płatem łączącym się wąską grzędą, ze zwartą centralną częścią Wyżyny Meghalaya i ograniczony głębokimi do 1000 m kanionami. Powierzchnia o rzeźbie pagórkowatej o deniwelacjach do 100 m opada od 1800 do 1100 m n.p.m. na odcinku 20 km. Rzeźba i ostre krawędzie płaskowyżu wiążą się z budową geologiczną. Starsze skały krystaliczne okrywają kilkusetmetrowej miąższości osady piaskowcowej facji litoralnej wieku kredowo-paleogeńskiego obejmujące kompleksy różnej odporności. Ku południowi jest ona zastępowana przez fację wapienną.

Wysokie opady sprzyjają ługowaniu składników odżywczych z płytkich i kwaśnych gleb, wykształconych na odpornym kompleksie skał osadowych (tab. 5). W okolicach Cherrapunji, o najsilniej zdegradowanych glebach formacje traw zajmują ponad 68% powierzchni (tab. 6), a poza ogródkami przydomowymi prawie nie spotyka się pól uprawnych. Lasy występują jedynie w postaci niewielkich płatów, będących przedmiotem kultu religijnego i podlegających ochronie. Obszar ten podlegał silnej antropopresji w ostatnich 200 latach. Powtarzający się, skrócony do 5 lat, cykl odłogowania spowodował wyjałowienie gleby i trwałe utrzymywanie się zbiorowisk trawiastych. Sprzyjają temu również coroczne wypalanie traw oraz intensywny wypas. Dodatkowymi czynnikiem przyspieszającym degradację jest odkrywkowa eksploatacja węgla kamiennego i wapieni.

6. CECHY RZEŹBY I ŚRODOWISKA EKSPERYMENTALNEJ ZLEWNI MAW-KI SYIEM

Zlewnia o powierzchni 22 ha leży w środkowo-południowej części Płaskowyżu Cherrapunji w wysokości 1314–1390 m n.p.m, ok. 1 km na zachód od stacji meteorologicznej w Cherrapunji. Zlewnię o długości 800 m budują żelaziste piaskowce przewarstwione mułowcami. Wysokości względne wahają się od 20 do 60 m. Gęstość sieci dolinnej jest znaczna, sięga 4 km, dlatego działy wodne są silnie rozczłonkowane, o stokach o nachyleniach 5–30°. Spłaszczenia i stromizny jak również schodowy profil dna doliny wiążą się ze zmienną odpornością ławic skalnych. Koryto potoku docięte jest do litej skały.

W zlewni przeważają gleby o zmiennej miąższości (0,25–1,5 m), na ogół płytkie, silnie zdegradowane. Warstwa powierzchniowa ma charakter gruboziarnistego bruku słabo przepuszczalnego. udział frakcji ilastej wzrasta z głębokością od 28 do 43%.

Podnóża stoków okrywa warstwa utworów deluwialnych o miąższości do 70 cm, a w samym dnie doliny poniżej odcinka erozyjnego miąższość aluwiów sięga 120 cm.

Sieć stałych cieków stanowi nieco niżej połowy sieci dolinnej. Większość cieków (poza głównym) jest okresowa i wysycha u schyłku pory suchej. Przeważającą część zlewni zajmują rzadkie lub gęstsze zbiorowiska trawiaste. Lasy i zarośla stanowią jedynie 16% powierzchni.

7. OPADY

Seria pomiarowa obejmuje już ponad 150 lat, ale jej jakość nie jest najlepsza. Deszczomierz w Cherrapunji znajduje się na wysokości 1302 m n.p.m., blisko południowej krawędzi Wyżyny Meghalaya, która opada pionowymi ścianami o wysokości ponad 1000 m. Krawędź ta jest pierwszą barierą na drodze monsunu. U podnóża Wyżyny, na terenie Bangladeszu roczne sumy opadów mieszczą się w granicach 3000–4000 mm, na krawędzi przekraczają 11 000 mm a 50 km w kierunku północnym, w Shillongu roczny opad wynosi tylko 2300 mm. Średni roczny opad wynosi 11 109 mm (za lata 1902–2000). Najwyższa suma roczna to 23 663 mm, najniższa 6283 mm. Miesiącami, w których zdarza się całkowity brak opadów są listopad, grudzień, styczeń i luty. Najwyższy zanotowany opad miesięczny to 8247 mm (lipiec).

Liczba dni z opadem wyższym od 2,5 mm wynosi średnio 159. Roczne sumy opadów w XX wieku wykazują niewielką tendencję dodatnią wynoszącą 16 mm/rok. Zmienność rocznych sum opadów jest mała. W latach 1902–2000 opady roczne przewyższające 15 000 mm wystąpiły 5 razy a opady niższe od 8 000 mm również 5-krotnie. Najwyższe roczne opady, od początku prowadzenia pomiarów zarejestrowano w 1974 i wynosiły one 23 663 mm. Jest to najwyższa na świecie zmierzona, roczna suma opadów. W 1984 opady lipca sięgnęły 9591 mm. Monsun w Cherrapunji rozpoczyna się średnio 29 maja i trwa do początku października. Średnia wysokość opadów w okresie występowania monsunu wynosi ok. 8600 mm. Na sumę składają się opady czerwca, lipca, sierpnia, września i opady z trzech dni maja i 5 dni października. Monsun rozpoczyna się gwałtownymi opadami o sumach dobowych rzędu 100–300 mm a kończy opadami o sumach 20–50 mm/dobę. Monsunowe opady stanowią 77% rocznej sumy opadów.

W okresie przedmonsunowym, w kwietniu i w maju występują opady o sumach, przekraczających 500 mm/dobę. Najwyższe sumy dobowe w czasie monsunu przekraczają 1000 mm. W dniu 16 czerwca 1995 roku spadło 1563 mm, co jest zbliżone do rekordu światowego, wynoszącego 1854,2 mm (Reunion, 15.III.1952). W dniu 15 czerwca 1995 roku spadło 930 mm co daje rekordową w skali światowej 2-dniową sumę opadów – 2493 mm.

W czasie monsunu intensywne opady rozpoczynają się w godzinach wieczornych i trwają do godzin porannych. Zastosowany w naszych badaniach w Cherrapunji niemiecki pluwiometr SEBA RG-50 (z cyfrowym rejestratorem RDS) o rozdzielczości czasowej 1 sekundy, rejestruje każdy opad o wysokości 0,1 mm. Opublikowane dotychczas wstępne wyniki analizy natężenia opadów w Cherrapunji wskazują na występowanie natężeń rzędu 40–70 mm/godz. W ciągu opadowym od 12 do 21 VI 2002 spadło łącznie 2160 mm, a rzeczywisty czas trwania opadu wynosił tylko 59 % całego okresu. Maksymalny opad godzinowy wynosił 72,5 mm (18.VI) a odpowiadające mu maksymalne natężenie 1,21 mm/min.

8. OBIEG WODY W ZLEWNI EKSPERYMENTALNEJ

Gleby zlewni Maw-ki Syiem są silnie zdegradowane, pozbawione górnych horyzontów i substancji organicznej, a w obrębie stoków mają charakter przemytych pokryw zwietrzelinowych. Na powierzchni występuje bardzo słabo przepuszczalna warstwa silnie scementowanego szkieletowego bruku powstałego w wyniku, długotrwałego bombardowania przez ekstremalne opady oraz wypłukiwania drobnych frakcji przez spływ powierzchniowy. W wielu miejscach pokrywa zwietrzelinowa została usunięta i na powierzchni występują skały podłoża.

Słaba przepuszczalność podłoża powoduje, że w początkowej fazie opadów szybko dochodzi do tworzenia się nienasyconego, hortonowskiego spływu powierzchniowego, co sprzyja przyśpieszonej transformacji opadów w odpływ. Po nasyceniu pokryw przechodzi on w spływ nasycony, który dominuje w okresie monsunu letniego i przyczynia się do szybkiego odprowadzania wody ze stoków. Natomiast na stale wilgotnych podnóżach stoków oraz w dnach dolin występuje on nieomal w czasie każdego opadu. Powierzchniowe warstwy pokryw są w stanie w ciągu około 3–5 godzin przechwycić opad o wysokości około 100 mm. Już na początku monsunu letniego wysokość opadów znacząco przekracza pojemność wodną pokryw. Część wody infiltruje systemem szczelin w podłoże skalne lub zostaje włączona w system krążenia związanego z krasem. Bardzo mała zdolność retencyjna płytkich pokryw powoduje, że w czasie opadów następuje gwałtowny wzrost przepływu w korytach, a po nim szybka regresja. Odpływ ze zlewni ułatwiają koryta z odcinkami podłóg skalnych.

9. NIEKTÓRE RELACJE MIĘDZY OPADEM A ODPŁYWEM

Obserwacje stanów wody i przepływów cieku Maw-ki Syiem miały charakter sporadyczny. Dają jednak ogólny obraz relacji opad-odpływ (tab. 14). Pobór wody do lokalnych wodociągów zakłóca obraz zmian z biegiem potoku. Pomiary dokonane w listopadzie wskazują na stopniowy wzrost przepływów w latach 1999–2001, co koreluje z czasem jaki upłynął od ostatnich intensywniejszych opadów (tab. 15). Listopadowy odpływ jednostkowy można szacować na ok. 0.01 $m^3km^{-2}s^{-1}$. Wyraźne jest wyczerpywanie zbiornika wód podziemnych w czasie pory suchej (o ok. 70–80% w ciągu 3 miesięcy).

W 2002 roku wykonano kilkadziesiąt pomiarów stanów wody na potoku Maw-ki Syiem (tab. 16, fig. 22). Stwierdzono gwałtowne wahania sięgające 2 m w ciągu doby. 26 czerwca 2002 roku woda przekroczyła znacznie 2 m i przelewała się przez most. Przepływ potoku oszacowano na 20–50 m^3s^{-1}. Gwałtowne spływy świadczą o niskiej infiltracji i małej zasobności zbiorników wód gruntowych.

10. PRZEWODNOŚĆ WŁAŚCIWA WÓD OPADOWYCH I PŁYNĄCYCH

Przewodność wód płynących jest pośrednio wskaźnikiem denudacji chemicznej. W ciągu trzech sezonów letnich stwierdzono występowanie w Cherrapunji „kwaśnych deszczy" czyli opadów o pH poniżej 5,6. Geneza kwaśnych deszczy w Cherrapunji jest trudna do wyjaśnienia i wymaga szerszych studiów. W dniach 2–4 lipca 2002 roku łączna suma opadów przekroczyła 320 mm, a pH wód opadowych zmieniało się od 5,40 do 3,30. Wysokie wartości pH, powyżej 5.0, występowały przy dużym natężeniu opadu, w godzinach nocnych. Najniższe wartości pH związane były ze słabymi opadami w występującymi w ciągu dnia. Przewodność właściwa wód opadowych mieściła się w przedziale 5,7–32,3 μS. Przeważają opady o niskim i skrajnie niskim przewodnictwie właściwym. Sporadycznie rejestrowano bardzo wysokie wartości. W połowie lipca 2002 roku wystąpiły natomiast opady o przewodności właściwej, przekraczającej 100 μS, co związane było z pojawianiem się w opadzie żółtego, mineralnego pyłu.

Wody cieków wykazywały silne zróżnicowanie w zakresie pH i przewodności właściwej. Odczyn wód w zlewni eksperymentalnej Maw-ki Syiem w lipcu 2002 r. mieścił się w przedziale 4,80–6,00 a przewodność 30–50 μS. Stwierdzono duże zróżnicowanie przestrzenne przewodności właściwej wód w zlewni Maw-ki Syiem, związane ze zróżnicowanym zasilaniem. Wody wypływające z młak i niewielkich, okresowych źródeł miały przewodność rzędu 60–80 μS. Wody większych cieków, o zlewniach 10 km^2, zasilanych z obszarów wapiennych miały przewodność rzędu 150–200 μS. Największe cieki, płynące w kanionach, o przepływie kilkudziesięciu metrów sześciennych na sekundę prowadziły wody o pH rzędu 6,0 i przewodności ok. 80 μS. Na tle niskich pH i niskiego przewodnictwa właściwego wód płynących piaskowcowego Płaskowyżu Cherrapunji, wyróżniają się cieki na południowym skłonie, zasilane z głębokich poziomów w wapieniach i skałach metamorficznych. Wody cieków w okolicy Laitkynsew mają pH rzędu 7,0 i mineralizację 250–450 μS.

11. EROZJA GLEB W ZLEWNI EKSPERYMENTALNEJ

Pomimo bardzo dużej energii ekstremalnych opadów erozja gleb i dostawa drobnoziarnistych zwietrzelin do koryt jest bardzo mała. Jest to związane z występowaniem na powierzchni, silnie scementowanego szkieletowego bruku, pozbawionego frakcji spławialnych. Ogranicza on skutecznie procesy rozbryzgu gleby i spłukiwania. Badania metodą cezu-137 wskazują, że erozja gleb nie przekracza 0,21 kg m^{-2} r^{-1}, a depozycja deluwiów u podnóża porośniętych trawami stoków nie przekracza 1,5 mm r^{-1}. Pokrywa traw stanowi skuteczny filtr w transferze sedymentu ze stoków do koryt.

Badania procesów erozji i transferu sedymentu mają istotne znaczenie w zakresie poznania wpływu dużej częstotliwości opadów na relaksację systemu fluwialnego. Współczesną cechą tego obszaru jest bardzo mała produkcja, przygotowanie i udostępnianie spławialnych cząstek w stosunku do potencjalnych możliwości erozyjnych ekstremalnych opadów. Efektywna geomorfologicznie dostawa zwietrzelin do koryt związana jest głównie z erozją linijną rozcięć erozyjnych na stokach inicjowanych głównie eksploatacją węgla, jak również z pogłębianiem koryt. Nawet podczas ekstremalnych wezbrań koncentracja transportowanej w korytach zawiesiny jest niewielka. Znaczącą część stanowi materiał organiczny pochodzący z pokrytych trawą stoków. Z powodu dużej częstotliwości ekstremalnych wezbrań skalne koryta są stabilne, a ich przekroje hydrauliczne dostosowane do ekstremalnych przepływów. Procesy erozji koryt są ograniczone niedoborem żwirowych frakcji rumowiska, które jest powszechnie eksploatowane.

12. WNIOSKI

1. CHARAKTERYSTYCZNE CECHY REJONU CHERRAPUNJI

Południowa część Płaskowyżu Cherrapunji budują w przewadze poziomo ułożone piaskowce (na obrzeżu także wapienie), które ukierunkowują odpływ i erozję sięgającą odporniejszych ławic. Młode podniesienie wzdłuż uskoków doprowadziło do wytworzenia progu tektonicznego rozciętego głębokimi kanionami. Ta krawędź Wyżyny otrzymuje rekordowe opady roczne 7000–24 000 mm skoncentrowane w miesiącach letnich. Sezonowość opadów monsunowych odbija się w obiegu wody, erozji gleb i produkcji biomasy.

Wylesienie i gospodarka żarowo-odłogowa w przeszłości doprowadziły na Płaskowyżu Cherrapunji przez przyspieszony spływ do zdarcia gleby i zastąpienia dawnego tropikalnego lasu zbiorowiskami trawiastymi. Zbiorowiska te są nadal niszczone przez nadmierny wypas i wypalanie. Do degradacji powierzchni Płaskowyżu przyczynia się również eksploatacja węgla i piaskowca w części północnej, a wapienia w południowej.

2. *DŁUGOOKRESOWE TENDENCJE EWOLUCJI KRAJOBRAZU*

Najstarszym elementem rzeźby jest pagórkowata powierzchnia wyżyny z miąższą pokrywą laterytowej zwietrzeliny wieku neogeńsko-czwartorzędowego. Po utworzeniu wysokiego progu tektonicznego, nadal aktywnego, nastąpiło jego rozcięcie wodami rzek spływających z wyżyny. Powstały głębokie kaniony poprzez cofanie się progów wodospadowych. Pogłębianie postępuje stopniowo w górę rzeki. Obecność odpornych ławic doprowadziła do powstania schodowej rzeźby grzbietów i stoków z progami denudacyjnymi i płaskich den dolin. Cofające się stoki stabilizowane są przez zsuwające się bloki skalne.

Postępujące wylesienie w połączeniu z gospodarką żarowo-odłogową w ostatnich stuleciach jak i bezpośrednie usuwanie gleby związane z eksploatacją surowców mineralnych, wystawiło odsłoniętą powierzchnię na działanie deszczu, spływ i erozję gleb. W efekcie tylko niewielka część pierwotnych zwietrzelin laterytowych i pokryw koluwialnych uchowała się. Rozprzestrzenianie się zbiorowisk trawiastych, ich nadmierny wypas i pożary doprowadziły do powstania na zdegradowanej powierzchni albo warstwy bruku złożonego z gruboziarnistego rumoszu i rezydualnych konkrecji żelazistych albo nawet odsłonięcia litej skały.

3. *WSPÓŁCZESNE PROCESY*

Reżim klimatyczny obszaru o ekstremalnych opadach decyduje o sezonowości procesów fizycznych i chemicznych. Można wydzielić trzy wyraźne pory roku: Suchą zimę, wiosnę z nielicznymi ulewami i deszczowe lato trwające 4–5 miesięcy z częstymi opadami rozlewnymi i ulewnymi. Corocznie opady dobowe przekraczają 500–700 mm. W ostatnim dziesięcioleciu obserwuje się wyraźny wzrost sum dobowych.

Silnie zdegradowana gleba i brak gęstej szaty roślinnej ułatwiają spływ powierzchniowy ukierunkowany osiami rozcięć. Warstwa powierzchniowego bruku lub podłoże skalne z warstwą żelazistą ograniczają infiltrację do najwyżej 20–30 mm/godz. W warunkach częstych ulew niemal codziennie dochodzi do hortonowskiego nasyconego spływu powierzchniowego. Na przykład w ciągu kolejnych 10 dni, w czerwcu 2002 roku, wielkość infiltracji została przekroczona co najmniej w ciągu 30 godzin. Jedynie część tej spływającej wody mogła być zatrzymana w trawach u podnóża stoków, w przewadze spływała ona skalnymi korytami. Dlatego obserwujemy gwałtowne wzrosty i spadki poziomu wody. procent wody magazynowanej w podłożu jest nieznaczny ale z nielicznych pomiarów przepływów w zlewni Maw-ki Syiem wnioskujemy, że przepływy stopniowo maleją w czasie pory suchej jesienią i odpływy jednostkowe spadają do rzędu 0,01 $m^3km^{-2}s^{-1}$. Szacunki przepływów powodziowych sięgających do 100 $m^3km^{-2}s^{-1}$ wskazują na to, że należą do najwyższych w świecie.

Badanie erozji gleb i transportu w rejonie Cherrapunji stwarza wyjątkową możliwość określenia wpływu dużej częstotliwości ekstremalnych opadów na produkcję i uruchomienie rumowiska jako wskaźników czasu relaksacji systemu fluwialnego. Wstępne wyniki wskazują, że jedynie niewielkie ilości gleby są uruchamiane na zadarnionych stokach i składane u ich podnóża. Brak współczesnej depozycji ^{137}Cs w profilu podłużnym stoku sugeruje, że wskaźniki denudacji stoków są bardzo niskie. Rozkład ^{137}Cs w profilach pionowych podnóży stoków wskazuje na tempo sedymentacji do 1,5 mm/rok. Gęsta pokrywa trawiasta podnóży stoków i den dolin zatrzymuje niesiony materiał. W procesie denudacji istotniejszą rolę odgrywa powierzchniowy pancerz niż energia spadającego deszczu. Odstępy czasu między ulewami są za krótkie aby doszło do wytworzenia zwietrzeliny zdolnej do odprowadzenia.

Jedynie w obszarach świeżo rozciętych przez wąwozy lub odsłoniętych przez eksploatację, powierzchniowy transport jest wyższy i nawet frakcja żwirowa bywa przemieszczana i składana w obniżeniach.

Tempo denudacji chemicznej na piaskowcach jest znacznie niższe niż na wapieniach. Nieliczne pomiary pozwalają ją oszacować na rzędu 200 t $km^{-2}rok^{-1}$.

W korytach potoków wyciętych w skale transport materiału wleczonego ograniczony jest do odcinków o większym spadku. Tworzenie skorup żelazistych na ławicach skalnych w porze suchej sprzyja bocznemu poszerzaniu koryt. Dlatego koryta bywają nieproporcjonalnie szerokie w stosunku do przepływów. Podcinanie brzegów prowadzi ostatecznie do umocnienia brzegów przez zsuwające się bloki. Erozja wsteczna wyraźna jest w głowach głębokich kanionów, gdzie obrywy i zerwy towarzyszą wodospadom.

Porę suchą charakteryzuje ograniczona działalność procesów. Na odsłoniętych powierzchniach parowanie sprzyja wytrącaniu się żelaza i manganu i tworzeniu skorup żelazistych typowych dla strefy pustynnej. Zapewne dawniej szata leśna lepiej chroniła glebę przed degradacją. Uprawa ziemi, wypas i eksploatacja powierzchniowa surowców wraz z erozją deszczu i spływem powierzchniowym przyspieszyły degradację gleb. Procesy te usunęły drobne cząstki gleby i doprowadziły do powstania odpornej warstwy na powierzchni. Często gleby zachowały jedynie warstwę rumoszową.

Ekstensywne użytkowanie w warunkach ekstremalnych opadów monsunowych doprowadziło w efekcie do powstania nowego sterylnego i stabilnego układu z wysokim spływem powierzchniowym, minimalnym odprowadzaniem substancji mineralnych i niską produkcją biomasy.

Układ ten obejmuje zarówno procesy charakterystyczne dla klimatu monsunowego, jak i dla warunków pustynnych. Koegzystencja tych procesów stała się możliwa dzięki wzmożonej różnorodnej ingerencji człowieka jak też specyficznym warunkom litologicznym i geomorfologicznym. Jest kwestią otwartą kiedy ten „sterylny" system ukształtował się. Może jest on produktem kilku stuleci, albo tylko dwóch ostatnich jak sugerowałyby ślady dawnych pól uprawnych wokół Cherrapunji.

4. MOŻLIWOŚCI ODBUDOWY ZASOBÓW NATURALNYCH

Zagadnienie renaturalizacji zdegradowanych geoekosystemów było podnoszone od dawna przez wielu przyrodników. W przypadku zasadniczo zmienionych układów, które osiągnęły stadium „sterylne" każde działanie zmierzające do odbudowy zasobów wodnych, glebowych i w końcu roślinnych winno być dokonywane bardzo ostrożnie, zaczynając od prób na poletkach i w małych zlewniach.

Odnowa zasobów wodnych, podstawy życia organizmów jak i różnych gałęzi gospodarki i dobrobytu ludności winna koncentrować się na wzroście retencji i ograniczeniu spływu. Powiększenie zasobów wód gruntowych może nastąpić przez powiększenie infiltracji przy pomocy stałej szaty roślinnej i warstwy glebowej. Powierzchniowa retencja może wzrosnąć przez budowę małych zapór i zbiorników wykorzystywanych też jako stawy rybne. Równocześnie trzeba by wprowadzić ostre przepisy ochrony czystości wód.

Odnowa szaty roślinnej może być wprowadzana stopniowo. W tak silnie zdegradowanym środowisku gatunki rodzime można by wprowadzać na niewielką skalę. Bardziej korzystnie byłoby zacząć od traw i drzew akceptujących porę suchą. Cechy fizyczne i obieg wody w glebie jak i braki drobnych frakcji gleby i niedobór soli mogą być głównymi barierami w przeprowadzeniu zalesień. W pierwszym zatem rzędzie należałoby zakazać takich praktyk jak wycinanie drzew, wypalanie i nadmierny wypas, co mogłoby dać efekty już po kilku latach. Najtrudniejsza jest odnowa gleb, w sytuacji zdarcia horyzontu A i powstania na powierzchni warstwy bruku. Należałoby zakazać eksploatacji glin namytych w obniżeniach. Tylko odnowa szaty roślinnej pozwoli odbudować glebę. W skali lokalnej można próbować kruszyć i usuwać kamienistą warstwę wierzchnią.

Aby odpowiedzieć na te pytania i odnowić zasoby naturalne obszaru o najwyższych na świecie opadach niezbędna jest bliska współpraca przedstawicieli różnych dyscyplin przyrodniczych i praktyków. Z naszej strony potrzebne są bardziej precyzyjne dane o zasięgu, skali i mechanizmach procesów przyrodniczych w warunkach nadmiernej eksploatacji zasobów naturalnych, która doprowadziła do powstania układów „sterylnych".

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