Hindu Kush - Himalayan FRIEND 2000-2003

United Kingdom Contribution to the International Hydrological Programme (IHP) of UNESCO
Hindu Kush – Himalayan
FRIEND 2000-2003

United Kingdom Contribution to the International Hydrological Programme (IHP) of UNESCO

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DFID
Department for International Development

Centre for Ecology & Hydrology
NATURAL ENVIRONMENT RESEARCH COUNCIL

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Foreword

It is increasingly apparent that technical advances alone cannot solve world water problems and that an interdisciplinary approach relating water and social issues is required. This view is reflected in the focus of the sixth International Hydrological Programme of UNESCO (2002-2007) on “Water interactions: systems at risk and social challenges”. The activities described in this report, conducted under the auspices of the Flow Regimes from International Experimental and Network Data (FRIEND) project (one of two “cross-cutting” themes in IHP-VI) are an important contribution to this Programme.

The cooperation between UNESCO and the UK Department for International Development (DFID) has enabled the United Kingdom to play a leading role in successive International Hydrological Programmes (IHP). The UK contribution has focused on FRIEND, an international regional hydrology project, which aims to improve the accuracy, consistency and ease with which water resources can be assessed through applied research addressing regional problems. A key element is the development of international cooperation leading to the exchange of data, knowledge and techniques between countries and regions. Over 100 countries now participate in eight regional FRIEND groups worldwide.

In 1996 a regional FRIEND project was initiated in the Hindu Kush – Himalayan region, bringing together hydrologists from Afghanistan, Bangladesh, Bhutan, China, India, Myanmar, Pakistan and Nepal for the first time. In a politically and environmentally sensitive area this was an important first step towards data sharing and scientific cooperation in hydrology. Funding by DFID from 2000 to 2003, administered by CEH Wallingford, UK, has ensured that the momentum developed at the start of HKH FRIEND has continued. It has led to a number of key achievements which are described in this report. These include developing a strategy for a Regional Hydrological Data Centre which will share data from across the region, the creation of two Focal Nodal Agencies in Nepal and Pakistan, the development of prototype IWRM software for estimating dry season flows in Nepal and the Indian State of Himachal Pradesh, and a range of training activities which have helped develop the hydrological capacity of the region.

The HKH FRIEND project provides a basis for continued participation of HKH hydrologists in the IHP and can continue to make an important contribution to improved management of water resources, which is the key to poverty alleviation in the Hindu Kush – Himalayan region.

Dr Alan Gustard
Chair, FRIEND Inter-Group Coordinating Committee 1998-2002
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<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tr>
<td>AARD</td>
<td>Average annual runoff depth (mm)</td>
</tr>
<tr>
<td>AHEC</td>
<td>Alternate Hydro Energy Centre, IIT Roorkee, India</td>
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<td>AOC FRIEND</td>
<td>West and Central Africa FRIEND</td>
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<td>AMHY FRIEND</td>
<td>Alpine and Mediterranean FRIEND</td>
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<tr>
<td>ASCII</td>
<td>American Standard Code for Information Interchange</td>
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<td>ASP</td>
<td>Active Server Pages</td>
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<tr>
<td>BfG</td>
<td>Federal Institute of Hydrology, Germany</td>
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<td>BUET</td>
<td>Bangladesh University of Engineering and Technology</td>
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<td>BWDP</td>
<td>Bangladesh Water Development Board</td>
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<tr>
<td>BWP</td>
<td>Bangladesh Water Partnership</td>
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<tr>
<td>CD</td>
<td>Compact Disk</td>
</tr>
<tr>
<td>CEH</td>
<td>Centre for Ecology and Hydrology, Wallingford</td>
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<tr>
<td>cumecs</td>
<td>cubic metres per second (m³/s)</td>
</tr>
<tr>
<td>CV</td>
<td>Coefficient of Variation</td>
</tr>
<tr>
<td>CWR</td>
<td>Crop Water Requirement</td>
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<td>DEM</td>
<td>Digital elevation model</td>
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<tr>
<td>DFID</td>
<td>United Kingdom Department for International Development</td>
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<tr>
<td>DHM</td>
<td>His Majesty’s Government of Nepal Department for Hydrology and Meteorology</td>
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<tr>
<td>DPR</td>
<td>Detailed Project Report</td>
</tr>
<tr>
<td>DWRE</td>
<td>Department of Water Resources Engineering (of BUET)</td>
</tr>
<tr>
<td>ENSO</td>
<td>El Niño – Southern Oscillation</td>
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<tr>
<td>ESRI</td>
<td>Environmental Systems Research Institute</td>
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<tr>
<td>ETo</td>
<td>Reference evapotranspiration</td>
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<tr>
<td>FAO</td>
<td>Food and Agriculture Organisation of the United Nations</td>
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<tr>
<td>FDC</td>
<td>Flow duration curve</td>
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<td>FMS</td>
<td>Flow monitoring site</td>
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<td>FRIEND</td>
<td>Flow Regimes from International Experimental and Network Data</td>
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<tr>
<td>f.s.e.</td>
<td>Factorial standard error</td>
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<tr>
<td>ftp</td>
<td>File transfer protocol</td>
</tr>
<tr>
<td>GIS</td>
<td>Geographical Information System</td>
</tr>
<tr>
<td>GLOF</td>
<td>Glacial Lake Outburst Flood</td>
</tr>
<tr>
<td>GPS</td>
<td>Global Positioning System</td>
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<tr>
<td>GRDC</td>
<td>Global Runoff Data Centre (of WMO)</td>
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<tr>
<td>HIMURJA</td>
<td>Himachal Pradesh Energy Development Agency</td>
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<td>HKH</td>
<td>Hindu Kush – Himalaya</td>
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<td>HMG</td>
<td>His Majesty’s Government (of Nepal)</td>
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<td>HP</td>
<td>Himachal Pradesh, India</td>
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<td>HPSRB</td>
<td>Himachal Pradesh State Electricity Board</td>
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<td>IAHS</td>
<td>International Association of Hydrological Sciences</td>
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<td>ICIMOD</td>
<td>International Centre for Integrated Mountain Development</td>
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<td>ICSI</td>
<td>International Commission of Snow and Ice (of IAHS)</td>
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<td>ISO</td>
<td>International Standards Organisation</td>
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<td>IHP</td>
<td>International Hydrological Programme (of UNESCO)</td>
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<td>IIT</td>
<td>Indian Institute of Technology</td>
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<td>IWRM</td>
<td>Integrated Water Resources Management</td>
</tr>
<tr>
<td>JNU</td>
<td>Jawaharlal Nehru University, New Delhi, India</td>
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<tr>
<td>k</td>
<td>Recession constant</td>
</tr>
<tr>
<td>Kc</td>
<td>Crop coefficient</td>
</tr>
<tr>
<td>KAR</td>
<td>Knowledge and Research programme (of DFID)</td>
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<tr>
<td>MENRIS</td>
<td>Mountain Environmental Natural Resources Information System (of ICIMOD)</td>
</tr>
<tr>
<td>MF</td>
<td>Mean flow, the arithmetic mean of daily flows</td>
</tr>
<tr>
<td>MoU</td>
<td>Memorandum of Understanding</td>
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<tr>
<td>MS</td>
<td>Microsoft</td>
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<tr>
<td>MW</td>
<td>Megawatt</td>
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<tr>
<td>Acronym</td>
<td>Definition</td>
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<tr>
<td>OFDS</td>
<td>Office for Foreign Disaster Assistance (of the USA)</td>
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<td>OHP</td>
<td>Operational Hydrology Programme (of WMO)</td>
</tr>
<tr>
<td>PC</td>
<td>Personal Computer</td>
</tr>
<tr>
<td>PCRWR</td>
<td>Pakistan Council for Research in Water Resources</td>
</tr>
<tr>
<td>pdf</td>
<td>Portable document format</td>
</tr>
<tr>
<td>PhD</td>
<td>Doctor of Philosophy</td>
</tr>
<tr>
<td>Qo</td>
<td>Initial flow (at beginning of recession)</td>
</tr>
<tr>
<td>Q95</td>
<td>The 95 percentile flow, that is equalled, or exceeded, 95% of the time</td>
</tr>
<tr>
<td>R²</td>
<td>Coefficient of determination</td>
</tr>
<tr>
<td>RECCIS</td>
<td>Regional Centre for Climate Impact Studies (proposed)</td>
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<tr>
<td>REFRESH</td>
<td>Regional Flow Regimes Estimation for Small Scale Hydropower Potential</td>
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<tr>
<td>RHDC</td>
<td>Regional Hydrological Data Centre</td>
</tr>
<tr>
<td>RMSSE</td>
<td>Average root mean squared standardised error</td>
</tr>
<tr>
<td>RWG</td>
<td>Regional Working Group</td>
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<tr>
<td>SAGARMATHA</td>
<td>Snow and Glacier Aspects of Water Resources Management in the Himalaya</td>
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<td>SDV</td>
<td>Stream depletion volume</td>
</tr>
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<td>SOHAM</td>
<td>Society of Hydrologists and Meteorologists of Nepal</td>
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<tr>
<td>SRMSE</td>
<td>Standardised root mean square error</td>
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<tr>
<td>SQL</td>
<td>Structured Query Language</td>
</tr>
<tr>
<td>To</td>
<td>Recession start time</td>
</tr>
<tr>
<td>TC</td>
<td>Technical Committee</td>
</tr>
<tr>
<td>TU</td>
<td>Tribhuvan University, Kathmandu, Nepal</td>
</tr>
<tr>
<td>UK</td>
<td>United Kingdom</td>
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<tr>
<td>UNESCO</td>
<td>United Nations Educational, Scientific and Cultural Organisation</td>
</tr>
<tr>
<td>US</td>
<td>United States of America (USA)</td>
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<tr>
<td>USAID</td>
<td>US Agency for International Development</td>
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<tr>
<td>USGS</td>
<td>US Geological Survey</td>
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<tr>
<td>UTM</td>
<td>Universal Transverse Mercator (map projection)</td>
</tr>
<tr>
<td>WARPO</td>
<td>Water Resources Planning Organisation (of Bangladesh)</td>
</tr>
<tr>
<td>WECS</td>
<td>Water &amp; Energy Commission Secretariat of the Ministry of Water Resources, Nepal</td>
</tr>
<tr>
<td>WMO</td>
<td>World Meteorological Organisation</td>
</tr>
<tr>
<td>WWW</td>
<td>World Wide Web</td>
</tr>
<tr>
<td>YWRC</td>
<td>Yangtze Water Resources Commission, China</td>
</tr>
</tbody>
</table>
Executive summary

The Hindu Kush – Himalayan (HKH) region extends some 3500 km across the northern part of the Indian sub-continent and includes the mountain territories of Afghanistan, Pakistan, India, Nepal, China, Bhutan, Bangladesh and Myanmar. The region is characterised by extremes of altitude, relief and climate. The strongly seasonal nature of the region’s climate results in an over-abundance of water in many areas during the wet, monsoon season and a scarcity of water in the dry-season. The region is home to nearly 150 million people, with more than three times as many living in the downstream plains of the mighty Ganges, Indus and Brahmaputra rivers. An adequate understanding of the flow regimes is extremely important in this region of increasing development and population pressures.

In a region of political disharmony, tensions between countries over the proper management and equitable allocation of water resources mean that the potential for international conflict is high. With many rivers originating in the HKH passing through several neighbouring countries before reaching the ocean, water resources planning is complicated and regional cooperation is essential to alleviate the threat of future conflict. The Hindu Kush – Himalayan FRIEND project was launched in 1996 to “aid the optimal utilisation and better management of the region’s water resources”, which are seen as the key elements for promoting cooperation and combating poverty in the region. The project seeks to improve the understanding of hydrological variability across time and space in order to develop practical methods for the sustainable management of the region’s water resources and for mitigating extreme hydrological events, such as floods and droughts. HKH FRIEND is one of eight regional projects of the FRIEND (Flow Regimes from International Experimental and Network Data) project, which is a component of the sixth International Hydrology Programme (IHP-VI) of UNESCO. In common with other regional FRIEND projects, HKH FRIEND has a demand-driven approach, where project activity and the direction of research is determined according to local needs. The project comprises a number of thematic research groups that are made up of individuals or groups of scientists undertaking research in the region.

The United Kingdom, through the Centre for Ecology and Hydrology (CEH) Wallingford, has played a leading role in the development of HKH FRIEND since its inception in the early 1990s. CEH’s recent contribution to the project has been funded through the 3-year DFID Water Theme project, “UK contribution to the IHP of UNESCO”. This report outlines, specifically, the activity and progress of the HKH FRIEND component of the project.

The activities supported by the project were determined in collaboration with stakeholders in the region. They were all targeted at improving the technical capability of local hydrologists to conduct research and to manage the region’s water resources more effectively. The sustainable management of water resources will ultimately lead to the alleviation of poverty in the region by ensuring a more reliable supply of freshwater to the many millions of people in the mountains and the plains beyond. The three key areas supported by the project were:

The development of the FRIEND HKH Regional Hydrological Data Centre (Chapter 3)

Compared to many other parts of the world, the density of national hydrological and meteorological monitoring networks in the Hindu Kush – Himalayan region is poor. By improving access to regional data, the capacity of local hydrologists to undertake meaningful analyses and assessments of the flow regimes and water resources will be greatly enhanced. The establishment of a Regional Hydrological Data Centre (RHDC), comprising hydrological and meteorological data from many countries of the region, has always been a priority for HKH FRIEND. As part of this project, a long-term strategy for the RHDC was drafted by local participants. It detailed the data requirements of the HKH FRIEND project, presented a
functional design specification for the RHDC and outlined a plan for its operational implementation. As part of this strategy, two Focal Nodal Agencies for the RHDC were appointed in Nepal and Pakistan. This vitally important first step should encourage other participating countries to establish their own focal agencies and contribute hydrological information and data. Meanwhile, the RHDC has proceeded to collate a metadata catalogue of the hydrological data that exists in the region. This information, on the availability of data and which organisations are responsible for it, will be of great use to anyone having an interest in Himalayan hydrology. Access to the catalogue is provided through an easily accessible World Wide Web portal. This facility will promote hydrological research and encourage national hydrometeorological agencies in the region to contribute data to the RHDC.

Development of regional low flow estimation methods for the HKH region (Chapter 4 and Chapter 5)

Reliable, practical methods for assessing and managing river flows are essential to ensure an adequate supply of water is maintained during the dry-season. Few of the hydrological studies that have been undertaken in the region are of use in the day-to-day management of water resources. The capacity for sustainable water resources management is further weakened by the lack of regulation of groundwater and surface water abstractions and discharges of effluent into streams, rivers and lakes. In collaboration with local partners, CEH developed a statistically based regional hydrological model for estimating average monthly dry-season flows in gauged or ungauged catchments for part of the HKH region. The models are a significant advance over the regional hydrological models that have previously been developed, as they describe the temporal sequence of flows during the critical dry-season months. The models were incorporated in a prototype software package to demonstrate the potential for effective water management in the region and applied to two selected “pilot” basins in India and Nepal. The software was also demonstrated at two stakeholder workshops in Kathmandu and Shimla (India) respectively in May 2003, attended by 42 participants including policy makers, water regulators, planners, engineers and academics. Encouragingly, participants at both workshops expressed a keen interest to develop the software further and each appointed a representative to consult with relevant ministries, regulatory bodies and others in order to develop a proposal for the operational implementation of the software. The response clearly shows that there is a pressing need for such tools in the region. Moreover, the project confirms that it is possible to develop robust hydrological models for assessing river flows at ungauged sites in the HKH, which can be applied successfully to provide powerful tools for improved water resources management.

Training and capacity building (Chapter 6)

The provision of training to local technical staff and hydrologists is an important feature of the HKH FRIEND project. Four regional training workshops were supported by the DFID project between March 2000 and April 2002, with a total of 66 people receiving training on such topics as Low flows, river quality monitoring or the application of geo-informatics in water resources management. Participant feedback showed that all of the courses were of practical use and would strengthen capacity in the region. The course format, of classroom lectures interspersed with practical group exercises and field excursions, proved very popular. It was suggested that more courses of this type be held in the future. Several participants also recommended that the course-material be included in university undergraduate and post-graduate curricula. Another important capacity building activity was to sponsor a young hydrologist from the Department of Hydrology and Meteorology in Nepal as an extra-mural PhD student at the University of Birmingham. The PhD on “Regional estimation of flow regimes in Himalayan catchments” is due to be completed early in 2004.

Chapter 7 concludes that considerable impetus has been given to HKH FRIEND and that this project represents a substantial and highly effective contribution by the United Kingdom towards the implementation of the UNESCO IHP in the HKH region. The work presented in this report has contributed to three of the six research groups that comprise HKH FRIEND:
Database, Low Flows and Water Quality. Good progress has also been made by the other groups (e.g. Floods, Snow and Glacier Hydrology), which are outside the scope of this report. The level of activity and enthusiasm shown by local participants for international collaboration is indicative of the success of HKH FRIEND.

The project has clearly bolstered the capacity for hydrological research and sustainable water management in the HKH region by facilitating improved access to regional hydro-meteorological data, demonstrating the benefits of integrated water resources management and providing training in contemporary methods to young technicians and scientists. This will eventually contribute to the UK Government goal of poverty elimination, as outlined in the 1997 White Paper (DFID, 1997) and subsequent Strategy Paper (DFID, 2001). It will lead local authorities and agencies to improve their management of water resources to ensure a reliable and equitable supply of clean water for drinking and cooking, food production, power generation and industry, while also encouraging the safe and proper disposal of industrial effluent and human waste. The quality of water in the region’s rivers and lakes will be enhanced, bringing added benefits to human health and the environment.

However, it is evident that there is still scope for improving hydrological research and developing tools to enable sustainable water resources management and to mitigate the hazards of floods and drought. There is a common perception that climate change is occurring faster in high mountain areas than other parts of the world. The need to conduct further research on how variations in climate and hydrological regimes impact upon the environment and the lives of people in Himalayan river basins is, therefore, becoming increasingly important. Following discussions with local hydrologists, the following four areas were identified, and agreed, as future priorities for the HKH FRIEND project:

- **Establishment of a Regional Centre for Climate Impact Studies (RECCIS)**
  The Centre would provide a focal point for scientists throughout the region to meet to exchange knowledge and expertise on regional climate issues. It would seek to advance research on such issues as the impacts of deglaciation on water resources, effects of changes in rainfall distribution and potential changes to the frequency and spatial distribution of extreme hydrological events.

- **Training and capacity building**
  In future, greater emphasis would be given to the dissemination of training to ensure maximum potential impact in terms of numbers of people reached. This would be achieved through: developing self-help training material; conducting training courses for trainers; developing university curricula; supporting post-graduate studies; and disseminating hydrological research effectively.

- **Tools for improved water resources management**
  A hydrological toolbox should be established, which would enable appropriate hydrological models to be identified, developed and applied at different locations in the HKH region. To demonstrate their effectiveness, toolbox components would be tested in contrasting river basins in Bangladesh, Bhutan, China, India, Nepal or Pakistan.

- **Development of the Regional Hydrological Data Centre**
  The next phase of the development of the RHDC will be devoted to extending its data coverage and strengthening the data network. The improved access to data would facilitate the hydrological research that is required to develop water management in the region.
1 Introduction

H.G. Rees

1.1 The Hindu Kush – Himalayan region

The Hindu Kush – Himalayan (HKH) region extends some 3500 km across the northern part of the Indian sub-continent, sweeping south-eastwards from 70° to 105°E in a broad arc between 25° and 40°N latitude. It includes the mountain territories of Afghanistan, Pakistan, India, Nepal, China, Bhutan, Bangladesh and Myanmar. Encompassing the Himalaya and Hindu Kush mountain ranges, the region is the source of the mighty Ganges, Indus and Brahmaputra rivers. It is bounded by broad fertile plains to the south and by the arid Tibetan Plateau to the north.

Figure 1.1 The Hindu Kush – Himalaya (HKH) region

The region is characterised by extremes of altitude, relief and climate. As a consequence, the hydrology of the region is quite different from most other parts of the world. Altitude varies dramatically over a relatively short horizontal distance of about 150 km, from about 50m in the plains to the south to over 8000m in the high mountains. The extreme relief results in a complex mosaic of topo-climates (Alford, 1992) that are determined by variations in slope, aspect and altitude. These range from the sub-tropical climates in the southern plains, to the temperate climates of the middle hills and arctic climates in the high mountains. The main controls on climate, however, are the weather systems that move in from the south-east during the summer and from the west in winter. The summer monsoon, which brings moist air up from the Bay of Bengal, normally commences in mid-June and lasts until mid-September. Mountain ranges block the northward advancement of the monsoon, causing widespread and intense rainfall on southern slopes, whereas on the leeward side of the mountain ridges, drier conditions prevail.
The onset of the monsoon is delayed and precipitation decreases along the Himalayan arc from east to north-west. There is also a general decrease in precipitation from south to north, with each successively higher mountain range featuring windward maxima and leeward rain-shadows that culminate in the high-altitude aridity of the Tibetan plateau. From November to April, westerly winds bring further precipitation, especially to the west. Annual average rainfall varies considerably across the region. While some of the highest annual rainfall totals on Earth are experienced on the southern slopes of the Eastern Himalayas, other areas to the west receive as little as 50 mm a year.

The strongly seasonal nature of the region’s climate results in an over-abundance of water in many areas during the wet monsoon season and a scarcity of water in the dry-season (Chalise, 2003). Floods and droughts are endemic to the region and regularly dominate the headlines of newspapers in the region. The region has witnessed major floods in Bangladesh in 1987 and 1998, the Indus basin floods of September 1992 in Pakistan and the Bagmati flood of July 2000 in Nepal. Such floods invariably result in disastrous land-slides that add significantly to the high death toll of such events. Water scarcity in the dry-season is another perennial problem that is compounded if the preceding monsoon is weak. A succession of weak monsoons, as has occurred in the north-western states of India in recent years, gives rise to widespread drought and potentially famine.

1.2 The human dimension

The Hindu Kush and Himalayan mountain ranges are among the largest reservoirs of freshwater in the world and are the source for the three major rivers of south Asia: the Indus, Ganges and Brahmaputra. The region is home to nearly 150 million people, with more than three times as many living on the downstream plains relying on its water to sustain their lives and livelihoods. The freshwater from the HKH is a critical resource for south Asia as a whole. A large proportion of the population depends on agriculture for their livelihood and, therefore, reliable access to this freshwater resource is a fundamental factor in influencing the level of poverty for many millions of people (Moench et al., 2003). A supply of clean freshwater for drinking, cooking and washing is essential for the personal hygiene and health. Adequate quantities of the resource are required to ensure that the disposal of effluent and waste into freshwater bodies is harmful neither to the environment nor to water users downstream. Reliability of water supply in the high-energy mountain rivers and streams is also important for hydropower production. It is a critical factor in determining whether the countries of the region can meet the increasing energy demands to maintain economic growth and combat poverty. Although the HKH is considered immensely rich in water resources (Chalise, 1993), the growing population and rapidly increasing demand for water, due to rural, urban and industrial development, are exerting immense pressure on the water resources of the region.

The flow regimes of the rivers that emerge from the HKH are dominated by the monsoon. The flooding that occurs during the wet season renders millions of people homeless annually, claims several hundred lives and causes millions of dollars worth of damage to property and the economy. It is the poorest in society who are the most adversely affected as they are least able to adapt and inhabit inadequate shelters in areas of greatest risk. In the dry-season, competition for water is at its highest and the demands for water often exceed the available supply. Generally there is little regulation of freshwater abstractions, either from surface-water (rivers or lakes) or groundwater (aquifers) sources, and few, if any, controls on the discharge of effluent to these water bodies. Consequently, water shortages, which could have been avoided with proper management, are frequent and the quality of the remaining water is appallingly low. Again, it is the poor who are the worst affected by these water shortages. It is they who have the least access to public water supply and sewerage networks and rely most on water from local wells, rivers or lakes, which are often polluted. Unsurprisingly, the incidences of, and death from, water-borne diseases, such as dysentery, cholera, giardia and malaria, is highest among the poor.
The hardship endured by people in rural mountain areas, caused directly or indirectly by floods, land-slides and problems of water scarcity, has contributed to an outward population migration to the cities. This has numerous social, economic and cultural implications for both mountain and urban areas. Up to 85% of the migrants are male, leading to a rapid growth in the proportion of women in the mountains, who, along with their children, are faced with an increasing burden of poverty (Ives, 1997). Yet, some 25-40% of the urban population in developing countries already live in impoverished slums, with little or no access to water and sanitation (World Bank, 1997). The influx of migrants from mountain areas, combined with the growth of the incumbent population, places considerable stress on the urban infrastructure to supply adequate clean water and sewage disposal.

In a region of such political disharmony, tensions between countries over proper management and equitable allocation of water resources mean that the potential for international conflict is high. With many rivers originating in the HKH passing through several neighbouring countries before reaching the ocean, water resources planning is complicated and regional cooperation is essential to alleviate the threat of future conflict.

1.3 The HKH FRIEND project

An adequate understanding of the flow regimes of this highly energized and fragile environment is extremely important as development and population pressures increase. The Hindu Kush – Himalayan FRIEND project was launched in 1996 to aid the optimal utilisation and better management of the region’s water resources, which are seen as the key elements for promoting cooperation and combating poverty in the region. To this end, the project seeks to improve the understanding of hydrological variability across time and space in order to develop practical methods for the sustainable management of the region’s water resources and for mitigating floods and droughts.

The HKH FRIEND project is one of eight regional projects of the FRIEND (Flow Regimes from International Experimental and Network Data) project, which is a component of the sixth International Hydrology Programme (IHP-VI) of UNESCO. In common with other regional FRIEND projects, HKH FRIEND has a demand-driven approach, with project activities and the direction of research determined according to local needs. These are defined by the hydrological agencies represented on the HKH FRIEND Steering Committee. The project comprises six thematic research groups, made up of individuals or groups of scientists undertaking research in the region. Short-duration training courses have been identified as a particular requirement of the HKH FRIEND project because the processing, analysis and management of hydrological information has traditionally been hampered by the lack of trained personnel. Development of appropriate hydrological research activities has also been limited by a lack of expertise.

1.4 The UK contribution to HKH FRIEND

The United Kingdom, primarily through the activities of the Centre for Ecology and Hydrology, has played a leading role in the development of several regional FRIEND projects worldwide. It was responsible for initiating the first FRIEND project in Northern Europe in 1985 and was instrumental in the development of a FRIEND project in Southern Africa (Southern Africa FRIEND). CEH has actively supported the establishment of other regional initiatives in particular Hindu Kush – Himalayan FRIEND (HKH FRIEND), Mesoamerican and Caribbean FRIEND (AMIGO), the Nile Basin (Nile FRIEND), Asian Pacific FRIEND and others. It has provided guidance on the formal establishment of the HKH FRIEND project and has supplied both technical and financial support, since the inception of the project in the early 1990s. This contribution has largely been made possible by the support of the United Kingdom Department for International Development (DFID), through the Natural Environment Research Council.
Grant for International Scientific Cooperation (1985-97), and for two years subsequently by the DFID Knowledge Acquisition and Research (KAR) programme (Rees et al., 1999).

From April 2000, CEH participation in HKH and Southern African FRIEND regions has been funded through the DFID Water Theme project, “UK contribution to the IHP of UNESCO”. This funding has also helped to develop international cooperation through FRIEND and has supported some activities of the International Association of Hydrological Sciences (IAHS) and other UK initiatives within the framework of the IHP. This report covers specifically the activity and progress achieved in the HKH FRIEND component from 2000-2003.

The activities, determined in close consultation with stakeholders in the region, were aimed at helping to improve the sustainable management of water resources in the region and to ultimately ensure a more reliable supply of fresh, clean water to the many millions of people in the mountains and the plains beyond. To achieve this, it is generally acknowledged that there is a need for hydrological agencies within the region to improve their capabilities to properly assess, develop and manage their own water resources. Capacity building activities, through training and skill-transfer, therefore, featured strongly in the project’s work programme. Following discussions with Steering Committee members and local project participants, it was agreed that the resources of the new DFID project would focus on three key areas:

- **Development of the FRIEND HKH Regional Hydrological Data Centre**
  In comparison with many other parts of the world, the density of national hydrological and meteorological monitoring networks in the Hindu Kush – Himalayan region is poor and well below that recommended by the World Meteorological Organisation. Given the sparseness of data, the sharing of hydrological information and data between countries is crucial for developing an understanding of the hydrology of the region. By improving access to regional data, the capacity of hydrologists to undertake meaningful analyses and assessments of the flow regimes and water resources will be greatly enhanced. The establishment of a Regional Hydrological Data Centre (RHDC), bringing together hydrological and meteorological data from all countries in the region, is a priority for the HKH FRIEND project and was identified as a key area for support by the DFID project. Although there had been earlier attempts to set up the data centre at the International Centre for Integrated Mountain Development (ICIMOD) in Kathmandu, there had been no formal strategy for its future implementation. An initial activity, therefore, was to produce a strategy for the RHDC. Drafted by local participants, the strategy detailed the data required for research within HKH FRIEND, presented a functional design specification for the RHDC, and outlined a plan for its operational implementation and long-term sustainability.

- **Development of regional low flow estimation methods for the HKH region**
  Reliable, practical methods for assessing and managing river flows are essential to ensure that an adequate supply of water is maintained for irrigation, small-scale hydropower and public water supply during the dry-season. With the majority of the population of the HKH region relying on agriculture for their livelihoods, a shortage of water directly impacts on crop productivity and, hence, poverty. Few of the hydrological studies that have been undertaken in the region are of use in the day-to-day management of water resources. The capacity for sustainable water resources management is further weakened by the lack of control, or regulation, of freshwater abstractions from groundwater or surface water sources and the discharge of effluent into streams, rivers and lakes. A statistically-based regional hydrological model for estimating average monthly dry-season flows in gauged or ungauged catchments was developed. The model was incorporated into a prototype software package to show the potential for effective water management in the region. As well as estimating the natural availability of water at any location on a river, the user can use the software to allow for the artificial influences within a catchment (impoundments, abstractions or discharges). As such, the software provides a method for improving the management of...
water resources, helping to ensure that the demand for water at any location within a catchment does not exceed availability and identifying where problems of over-exploitation are likely to occur. The software was applied in two selected “pilot” basins in India and Nepal and demonstrated to groups of water regulators, planners and engineers in both countries.

- Training and capacity building

The need to provide training to local technical staff and hydrologists is considered a priority for the HKH FRIEND project. To address this, four regional training workshops were supported by the DFID project between March 2000 and April 2002. As detailed in Chapter 6, a total of sixty-six individuals received training on Low Flows, River Quality Monitoring or the Application of Geo-Informatics in Water Resources Management at courses in Bangladesh, India and Nepal. As a further contribution to long-term capacity, the project also sponsored (through meeting registration fees, tuition fees, travel and subsistence costs) a Nepalese hydrologist to complete a PhD at the University of Birmingham. This research entitled “Regional estimation of flow regimes in Himalayan catchments” has characterised hydrological and meteorological behaviour in the Himalaya, with view to improving the estimation of the river flows in ungauged catchments.

It is clear that considerable impetus has been added to the HKH FRIEND project as a result of these recent DFID supported activities. Chapter 2 provides the background to HKH FRIEND, while the strategy and progress with the implementation of the Regional Data Centre is described in Chapter 3. The development of the regional hydrological model and its implementation in the prototype IWRM software is described in Chapter 4 and Chapter 5 respectively. Chapter 6 outlines activities which have been undertaken to build capacity in the region, while Chapter 7 reviews the benefits of the work and the future of the project.
2 The HKH FRIEND project

M. Shrestha and S.R. Chalise

2.1 The evolution of HKH FRIEND

The evolution of Hindu Kush – Himalayan FRIEND began in 1989 when the International Centre for Integrated Mountain Development (ICIMOD) in Kathmandu, the UNESCO IHP and His Majesty’s Government of Nepal Department of Hydrology and Meteorology (DHM) jointly organised a Workshop on the Hydrology of Mountainous Areas. This led to the establishment of a Regional Working Group (RWG) on Mountain Hydrology in 1989, comprising representatives from countries of the region, UNESCO, the World Meteorological Organisation (WMO) and ICIMOD. The first consultative meeting of RWG was held in October 1990 in Kathmandu, which recommended that a regional project named “Regional Network of Experimental Watershed on Hydrological Studies” was established. UNESCO and ICIMOD were charged with preparing a proposal for the project. Although the proposal was endorsed at the second meeting of the RWG in March 1992, the project failed to materialise.

At the next meeting of the RWG in New Delhi in November 1993, efforts to launch a regional project were advanced when the relevance of a FRIEND (Flow Regimes from International Experimental and Network Data) project in the region was discussed. By this time FRIEND projects were well established in northern Europe, the Alpine and Mediterranean region of southern Europe and southern Africa, with others emerging in West and Central Africa and in the Asian Pacific region. Realizing that the objectives of FRIEND were compatible, a preparatory meeting to launch a FRIEND project for the HKH region was held in New Delhi in July 1995. Meeting participants included representatives from five of the eight HKH countries, UNESCO, the German IHP/OHP Committee and CEH. Suggestions were made relating to the objectives of the project, its name and organisation, and an interim working committee was set-up to finalise a proposal for the new HKH FRIEND project. The proposal was finally approved, and the HKH FRIEND project officially launched, at a meeting of national representatives from Afghanistan, Bangladesh, Myanmar, Nepal and Pakistan and others, including UNESCO, WMO and CEH, in Kathmandu on 23-24 March 1996.

2.2 Objectives of HKH FRIEND

2.2.1 Development Objectives

The primary objectives of the HKH FRIEND Project are to aid optimal utilisation and better management of the region’s water resources. It aims to promote productivity through agricultural activities, hydropower generation, which will ultimately lead to the reduction of poverty in the region. For this it is required to improve the understanding of hydrological variability and similarity across time and space so as to develop hydrological science and practical design methods, dealing with rainfall-runoff estimation, stream flow simulation, etc. It will enable a consistent set of flood and low flow design methods and procedures to be derived. There is also a need for consistent methods of analysis because of the difficulties that are encountered in comparing results between countries and regions.
2.2.2 Specific Objectives
The specific objectives of the HKH FRIEND project are:

- To improve understanding of the hydrological processes of the HKH region, with particular reference to upland-lowland linkages;
- To build capacity needed for scientific analysis of hydrological processes and to develop practical design methods for the HKH region;
- To promote data exchange between the countries of the region.

2.3 Execution of the project
Activities towards achieving these objectives are conducted by the following six thematic research groups within HKH FRIEND:

- Database
- Low Flows
- Floods
- Rainfall-runoff
- River Water Quality
- Snow and Glaciers

Each group has a coordinator and participants, from several different countries, who conduct individual or joint research relevant to the respective theme. These coordinators and participants are listed in Annex 1.1. Group activities and research are overseen by the HKH FRIEND Steering Committee, which meets approximately every two years. At Steering Committee meetings, coordinators present the progress of their groups and outline plans for future activity. The Steering Committee is responsible for ensuring that the work of the six groups is consistent with the stated objectives of the HKH FRIEND project and the UNESCO IHP.

The Steering Committee of the HKH FRIEND project formally consists of national IHP representatives from Bangladesh, Bhutan, China, Nepal and Pakistan and representatives from collaborating partner institutions, namely, the German National Committee for IHP/OHP, Global Runoff Data Centre (GRDC), CEH Wallingford, WMO, UNESCO and ICIMOD (see Annex 1.2). Although India has no formal government-approved representation on the Steering Committee, it is represented in an observer capacity by senior academics from the university sector. The coordinator of each of the six thematic research groups has as an observer status on the Committee. Participants from other international hydrology projects and regional FRIEND groups are also usually invited to participate at meetings as observers. The organisational structure of HKH FRIEND project is shown in Figure 2.1.

A new Chairman of the project is elected at every Steering Committee meeting, holding tenure for approximately two years. The day-to-day running of the project is undertaken by the HKH FRIEND Secretariat, which is hosted by ICIMOD in Kathmandu. Amongst its many duties, the Secretariat arranges Steering Committee Meetings, liaises with Steering Committee members, HKH FRIEND research groups and other FRIEND groups and projects. It also communicates activity between project participants, and supports group activities by identifying and obtaining funding for their various initiatives.

2.4 HKH FRIEND activities
Some of the activities undertaken within HKH FRIEND since its establishment in 1996 are summarised below.
Figure 2.1 Organisational structure of the HKH FRIEND Project

Figure 2.2 Participants in the HKH FRIEND Steering Committee Meeting, 7-8 May 2003
2.4.1 Development of the Regional Hydrological Data Centre (RHDC)
The RHDC was established during the First Steering Committee Meeting of the HKH FRIEND in May 1998. Details of its recent development are given in Chapter 3.

2.4.2 Training
As mentioned earlier, capacity building through training is an important feature of the HKH FRIEND project. Several highly successful training courses have been conducted over the last few years, as outlined below. Further details of those supported by CEH, as part of the DFID project “UK contribution to the IHP of UNESCO”, are given in Chapter 6.

  Training on hydrological database management was provided to 12 participants from Bangladesh, China, India, Nepal and Pakistan, with the support of staff from the Global Runoff Data Centre, Koblenz, Germany.

  A four-day training programme on low flow methods was provided to 15 participants from five HKH countries, supported by CEH, UNESCO and ICIMOD.

  Topics covered included source of pollution, water quality parameters (physical, chemical, biological, microbiological), water quality standards and contaminant transport. With support from the German IHP/OHP committee, training was provided to 12 scientists and hydrologists from Bangladesh, Nepal and Pakistan.

  Two training courses were conducted by CEH Wallingford in Roorkee, India and Dhaka, Bangladesh, attended by a total of 36 young hydrologists and technicians (see Chapter 6).

- Training on Glacier Mass Balance, India, September 2002
  Training on Glacier Mass Balance Measurement was organized by the Jawaharlal Nehru University with the support of UNESCO, the International Commission for Snow and Ice (ICSI), HKH FRIEND and the Department of Science and Technology of the Government of India in New Delhi. Twenty participants from India, Bhutan and Nepal attended and lecturers came from Austria, Germany, Sweden, Japan, France and India. Two days of lectures in Delhi were followed by hands-on training on the Chhota Shigiri glacier in Himachal Pradesh (see Figure 2.3).

2.4.3 Meetings/Workshops
Several meetings and research group workshops have been conducted, which provide an opportunity for project participants to exchange knowledge and ideas on new research, discuss future activities and formulate research proposals for approval by the Steering Committee. These include:

- First Steering Committee Meeting, March 1998;
- Inception Workshop of the Database Group, March 1999;
- Inception Workshop of the Snow and Glacier Group, March 1999;
- Workshop of the Low Flow Group, April 1999;
- Second Steering Committee Meeting, April 2000;
- Third Steering Committee Meeting, May 2003.
2.4.4 Research Projects

Some of the research projects being conducted within HKH FRIEND, which are outside the scope of this report include:

- **Snow and Glacier Aspects of Water Resource Management in the Himalaya**
  All HKH rivers are glacial in origin. With the apparent deglaciation in the Himalayas, this DFID funded project is of great significance to future water resources management in the region. The project comprises two distinct elements: development of a regional runoff model incorporating a suitable snow/glacier melt component; and a socio-economic assessment of the potential impact of deglaciation, brought about by climatic changes, on the livelihoods of people in this region.

- **Regional Flow Regimes Estimation for Small-scale Hydropower Assessment**
  India and Nepal are presently facing an acute power shortage. The aim of this DFID sponsored project was to develop reliable and consistent methods for estimating the hydrological regimes at ungauged sites in the Himalayan and the sub-Himalayan region of India and Nepal in order to assess the hydropower potential of such sites. Sales of the resulting hydropower estimation software are continuing with 76 copies sold to-date in India and Nepal.

- **Regional Cooperation for Flood Information Exchange in the HKH Region**
  The purpose of this USAID funded project is to devise a flood information system in which data and information can be shared regionally. The aim of the project is to devise appropriate flood mitigation measures to reduce the loss of life and property.

- **GIS application to Flood Risk Mapping**
  This UNESCO supported project explores the application of GIS to flood risk mapping in selected watersheds in Nepal. The objective of the study is to map flood risk and vulnerability and to identify disaster mitigation activities in order to reduce future loss of life and property. A key output will be an analytical report with a series of maps including hazards, exposure, risk, vulnerability, disaster and mitigation measures.
3 HKH Regional Hydrological Data Centre

R. Rajbhandari, B. Shrestha and H.G. Rees

3.1 Introduction

Since all the major rivers that originate in the Hindu Kush Himalaya (HKH) flow through many countries before reaching the ocean, cooperation between the countries on hydrological data is essential for water management and for understanding the hydrology of the region. Presently there is limited information sharing between countries. In some, hydrological information and other geographical data are even treated as classified. Access to useful hydrological information is very difficult for scientists of the region. In order to overcome these problems, the HKH FRIEND project has been striving to establish a Regional Hydrological Data Centre (RHDC) at the International Centre for Integrated Mountain Development (ICIMOD) in Kathmandu since 1998. The main objective of the RHDC is to build a hydrological and climatic database for the HKH region that would serve the different scientific research groups of the HKH FRIEND project and other research initiatives under the overall framework of FRIEND. Realising the need for such a database to facilitate high quality hydrological research in the region, the Centre for Ecology and Hydrology, as part of the “UK Contribution to the IHP of UNESCO” project, has been actively supporting the development of the RHDC. This chapter describes the progress achieved through this activity.

3.2 Establishing a strategy for the RHDC

Administratively, the development of the RHDC is the responsibility of the Database Group of the HKH FRIEND project. The Database Group is one of six thematic groups of the project (see Chapter 2). Participants of the Database Group include individuals, from different countries in the region, who have an active interest or involvement in hydrological data and its management. The activities of the Group are overseen by the Steering Committee of the HKH FRIEND project with meetings approximately every two years.

Although successive meetings of the HKH FRIEND Steering Committee in 1998 and 2000 had discussed the RHDC at length and had agreed terms and conditions for data exchange and dissemination, there was no document defining a plan for its implementation. In collaboration with ICIMOD, Database Group participants, Steering Committee members and CEH, a strategy for the future development of the Regional Hydrological Data Centre (RHDC) was developed. In determining the strategy, the following issues were addressed:

1) The data requirements of FRIEND HKH project participants;
2) The composition of the RHDC and whether and how it should include:
   a) a metadata catalogue of relevant time-series (hydrometeorological) and spatial (hydrometeorological, physiographical, etc.) data available in the HKH region;
   b) a database comprising time-series of hydrometeorological data (river flows, precipitation, and other data as identified in the review of data requirements);
   c) a GIS-based database comprising relevant spatial data-sets;
3) The computer hardware and software upon which the RHDC will be established;
4) The design, implementation and operation of the RHDC system;
5) Procedures, roles, responsibilities and rules for data acquisition, custodianship and data dissemination;

6) Accessibility of the RHDC data to FRIEND HKH project participants, including an assessment of the likely costs of any upgrades that may be required to existing hardware and software;

7) Staffing arrangements for the development and subsequent management of the RHDC;

8) Training requirements of RHDC staff and potential users and its provision;

9) The cost implications, both initially (e.g. capital purchase, system development, training, staffing) and in the long-term (e.g. maintenance, system upgrades, staff retention);

10) The sustainability of the RHDC under the proposed configuration (i.e. how will it be funded and managed beyond the term of the present sub-contract);

The Strategy Document was completed in October 2001 and was subsequently distributed between Steering Committee members for their approval. The document was formally endorsed by the Steering Committee in January 2002, with work towards implementing the strategy undertaken by the Mountain Environmental Natural Resources’ Information System (MENRIS) division of ICIMOD. According to the Strategy, the RHDC continues to operate under the overall guidance of the Database Group and is overseen by the Steering Committee. Close links are maintained with the HKH FRIEND Secretariat. Data experts from other regional FRIEND groups also provide guidance and technical advice as required. The RHDC serves to facilitate and co-ordinate the collection, exchange, processing and archiving of relevant hydrological data and information from participating institutions in the HKH region. Its activities are now focused on the following:

- to develop a regional hydrological database to serve the research needs of the HKH FRIEND project;
- to promote free exchange of data for research purposes;
- to develop a metadata catalogue of hydrological data available regions;
- to build regional capacity in hydrological data management, GIS and water resources management;
- to integrate the existing time database with GIS.

### 3.3 The RHDC Data Network

The agreed approach to the structural implementation of the RHDC is reflected in the data model shown in Figure 3.1. The model relies on Focal Nodal Agencies in each of the partner countries. These Focal Nodal Agencies are responsible for collating data from the primary sources in their respective countries and for forwarding them to the RHDC. The RHDC, in turn, maintains the database and interacts with the various users. The MENRIS division of ICIMOD are responsible for the day-to-day running of the RHDC, whereas policy and administrative aspects of the database network are the responsibility of the Database Group. The overall operation of the model is based on partnership and networking at the national and regional level. It may be considered as a network of networks, with the network of each regional country working as part of the larger regional network. Within this model, the Internet is the main medium for facilitating information sharing amongst the network partners.

In establishing the strategy for the RHDC, a questionnaire was prepared and distributed to HKH FRIEND participants to identify the types of hydrological and climatic data required. Daily rainfall and discharge (river flow) data were identified as the most important data types for all the research groups. The RHDC is committed to collecting and storing as much of this data as possible, by bringing together all available data sets, in collaboration with the Focal Nodal Agency network.
The appointment of a suitable Focal Nodal Agency in each country is a crucial part of the above model. A Focal Nodal Agency acts as a conduit for hydrological data and metadata from a given country to flow to the RHDC. In liaison with the HKH FRIEND Secretariat, the RHDC have expended a considerable effort to identify suitable organisations or individuals in each country. Two Focal Nodal Agencies have so far been established; the Department of Hydrology and Meteorology (DHM) for Nepal and the Pakistan Council for Research in Water Resources (PCRWR) in Pakistan. The Focal Nodal Agency in Nepal was established through a Memorandum of Understanding (MoU) between ICIMOD and Department of Hydrology and Meteorology (DHM). The signing of the MoU was a very important milestone in the RHDC’s activities and the event was highlighted by several national daily newspapers in Nepal (Figure 3.2). The MoU formalises the exchange of hydrological and climatic data for research purposes within the overall framework of HKH FRIEND and commits DHM to identify suitable representative river basins and provide daily hydrological and climatic data for FRIEND research. So far, the RHDC has received daily discharge data from over 50 gauging stations in Nepal.

Despite many communications and a consultation visit, it has not yet been possible to secure a Focal Nodal Agency in Bangladesh through the HKH FRIEND network. Recently, however, the Bangladesh Water Partnership (BWP) has expressed an interest to enter into joint collaboration with ICIMOD, particularly with respect to data sharing in the water resources sector. A MoU between ICIMOD and BWP is now being prepared and should hopefully be signed in the near future. This would make BWP the third established Focal Nodal Agency. Meanwhile, discussions are on-going with potential partners in other member countries of the region and copies of the MoU have been provided to them for review.

Figure 3.1 RHDC Data Model
3.4 Development of the database system

One of the primary objectives identified for the RHDC was to design and develop a World Wide Web based hydrological database system that would provide easy access to both “users” and “providers” of hydrological information. The outline design of the database is presented in Figure 3.3. The emphasis has been given towards building a web-compatible hydrological and climatic database, which was designed and developed using Active Server Pages (ASP) and Structured Query Language (SQL). The metadata catalogue provides a gateway to hydrological and climatic databases with a back-end database server – MS SQL server. An integration of GIS using ARCIMS (Internet Map Server) has been achieved to provide the visual GIS interface and also to superimpose the relevant GIS data layers such as drainage network, land-use, DEM, satellite imagery etc. As Figure 3.3 indicates, the RHDC may receive data from Focal Nodal Agencies in a variety of different layouts and formats, such as in ASCII, EXCEL or ACCESS. For loading onto the database all data are pre-processed into SQL Server format. The database system has been designed for easy navigation of the underlying data, which the user can view in either graphical (Figure 3.4) or tabular (Figure 3.5) format on a year-to-year basis.

Figure 3.2 Signing of the MoU between ICIMOD and DHM, Nepal

Figure 3.3 RHDC Database design
Figure 3.4 Sample data from RHDC database in graphical format

Figure 3.5 Sample data in tabular format
3.5 Status of the database

3.5.1 Hydrological and climatological time-series data

A summary of the time-series data that the RHDC has managed to acquire, via Focal Nodal Agencies, which is now available to HKH FRIEND project participants is shown in Table 3.1 below. Both gauged daily and monthly river flow data are available on the database, together with various climatological data sets. As more Focal Nodal Agencies are established, it is hoped that the temporal and spatial coverage of the data will be greatly improved in the near future.

<table>
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<th>Country</th>
<th>No. Stations</th>
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<th>Latest record</th>
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<td>258</td>
<td>1956</td>
<td>1996</td>
<td>20</td>
</tr>
<tr>
<td><strong>Monthly Rainfall</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bangladesh</td>
<td>22</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bhutan</td>
<td>23</td>
<td>1985</td>
<td>1999</td>
<td>4</td>
</tr>
<tr>
<td>India</td>
<td>26</td>
<td>1900</td>
<td>2001</td>
<td>56</td>
</tr>
<tr>
<td><strong>Monthly Temperature</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nepal</td>
<td>118</td>
<td>1957</td>
<td>1996</td>
<td>17</td>
</tr>
<tr>
<td><strong>Daily Discharge</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nepal</td>
<td>50</td>
<td>1964</td>
<td>2000</td>
<td>18</td>
</tr>
<tr>
<td><strong>Monthly Discharge</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>India</td>
<td>3</td>
<td>1958</td>
<td>1979</td>
<td>14</td>
</tr>
<tr>
<td>Pakistan</td>
<td>1</td>
<td>1968</td>
<td>1979</td>
<td>11</td>
</tr>
</tbody>
</table>

3.5.2 Metadata

Given the political sensitivities regarding hydrological data sets in the region, the emphasis during this phase of the project has been towards development of a metadata catalogue. Metadata is essentially data on data. One of the objectives of the RHDC is to inform HKH FRIEND participants of the existence of relevant data and where and how it may be obtained. As such, the data itself need not necessarily be physically stored and maintained by the RHDC and, thus, sensitivities over ownership and use are avoided.

Before a metadata catalogue of hydrological and climatological data can be built it is important to establish the type of information (metadata) that is required and how it should be stored and presented. International standards have been defined for the design and handling metadata (e.g. TC211/ISO19115) and the RHDC have been careful to observe these standards in the development of its metadata database. A metadata format was developed and adopted after circulating it to Steering Committee members, Database Group member and the coordinators of other thematic research groups. An example of the Metadata Entry Form, developed by RHDC for hydrological data, is shown in Figure 3.6. As well as metadata on hydrological data, the RHDC contains metadata on regional climatological data and spatial (map) data. RHDC metadata indicate whether the data are available at the RHDC or elsewhere and the restrictions, if any, on their use. Climatological stations of the HKH region, which appear in the RHDC metadata catalogue, can be viewed via a GIS interface that was developed specifically for the project (Figure 3.7).
Figure 3.6 Metadata entry form for hydrological data

Figure 3.7 GIS interface of the RHDC metadata catalogue
3.6 Deployment of RHDC database

Internet communication technology clearly provides the backbone to the implementation of the RHDC conceptual model, its database and the network for sharing information. Access to the data and information held by the RHDC is facilitated through its own WWW portal, http://www.hkh-friend.net/, which was designed and developed for the HKH FRIEND project and the RHDC as part of this DFID funded project. The home page can be seen in Figure 3.8.

The web site contains all relevant information pertaining to HKH FRIEND as well as the FRIEND project in general. The “Research Group” section of the web-site contains details of all on-going activities within each of the thematic groups, listing group participants and their contact details. Minutes of past meetings, technical reports and training course materials are all publicly available in PDF format. Links to other FRIEND web-site and other, water related, web-sites are also provided. The RHDC section of the web-site contains details of the RHDC database, its metadata and maps. Different kinds of climatic and hydrological maps are provided in the map sections of the RHDC. The portal has been designed in such a way that the window to the RHDC database is only through the metadata section. The web-site visitor has the option to view the metadata information sorted on various fields, such as, station number, station name, elevation, basin name, etc.. The returned metadata information clearly indicates the existence of the real data and, if it exists, a dynamic graph is displayed showing monthly values or statistics. Total values are given in the case of rainfall data, while mean values are given for discharge data. There is an option to hide the monthly values while viewing the graph. There is also provision to view the daily values. While displaying the data for a given station, other summary information, such as, data start and end year, station elevation and geographic coordinates, are also displayed.

![Figure 3.8 Home-page of the RHDC WWW portal](image)

The RHDC portal allows for the submission of metadata, using two kinds of form, namely the Climatic Archive Metadata Entry Form and Hydrological Archive Metadata Entry Form (see Figure 3.6). Once submitted, the metadata reside in a temporary file for the database manager to review before being merged into master metadata database.
Data may also be requested through the RHDC portal. Once the Data Request link is selected, an interactive form is provided to the user, requesting details of the type and duration of data required and the rationale for the request. As some of the data has been provided to the RHDC on the condition that it may only be used for research within HKH FRIEND, not all requests are fulfilled. If the request is allowed, the data is deposited on the ftp site of the HKH FRIEND project, where it remains for a specified period. The data requestor is informed by e-mail.

3.7 Future activities of the RHDC

Although significant advances have been made with the RHDC over the last three years, much work remains to firmly establish it as the pre-eminent repository of data and information for hydrological research in the HKH region. The future success of the RHDC will depend heavily on the provision of data from its partner countries via the Focal Nodal Agency network. The success in establishing two (Nepal and Pakistan), or possibly three (Bangladesh), Focal Nodal Agencies to-date is a real achievement in such a politically sensitive region. The increased volume of data that will flow to the RHDC from these Agencies, and the value of this data to regional hydrological research, will demonstrate to other countries the benefits of collaborating on data exchange. The RHDC will, therefore, encourage existing Focal Nodal Agencies to provide more data, while, at the same time, continuing in its attempt to identify and persuade appropriate organisations in other countries to join the network. However, given the political problems of the region, such activity will require a considerable amount of tact, diplomacy and patience. Keen interest has been shown in RHDC activities within the region and many have expressed a willingness to collaborate. The RHDC should, therefore, remain optimistic that further good progress can be expected in the near future.

In the meantime, it will be important to continue the technical development of the RHDC, to make sure that the data that is currently available is easily accessible to HKH participants. Data acquisition and dissemination will continue be an important activity for the RHDC. Populating the RHDC with metadata and hydrological data will be an on-going process, as will be the improvement of dissemination pathways via the RHDC web portal. MENRIS has many spatial data coverages of the HKH region, including digital maps of land cover, administrative boundaries, watersheds, river networks and water bodies. It also has many satellite images and digital elevation models (DEM), such as the DEM of Nepal at the scale of 1:250,000. These data and that resulting from ICIMOD projects will soon be integrated into the RHDC database and made available for HKH FRIEND research.

The training of regional staff on aspects of data management and use will remain a priority for the RHDC. RHDC-led training courses such as the one described in Chapter 6, on the “Application of Geo-Informatics for Water Resources Management”, help enormously towards building the capacity of regional organisations to effectively manage water resources. Subject to funding, many similar courses will be conducted by the RHDC in the future.

For all these planned activities, financial support will be necessary. The RHDC is particularly grateful for the funding provided to it by DFID and would, of course, welcome any future support. However, it is aware that such direct funding may not always be forthcoming and, as part of its strategy, has considered possibilities for making the RHDC more financially self-sufficient. One possible option may be the development of “value added products” from the HKH FRIEND data that would be sold and provide a source of income. Products could include outputs from the analysis of time-series (e.g. regional flow duration or flow frequency curves) and high-resolution GIS coverages derived from complex satellite imagery (e.g. land-cover maps, snow-line maps, etc.). Other options include incorporating RHDC development as an element of other potentially well-funded regional initiatives, such as the prospective HKH Regional Flood Forecasting System. Staff at MENRIS are committed to the continued development of the RHDC and will continue to actively pursue any opportunities which arise.
4 Regional low flow estimation

*M.G.R. Holmes, H.G. Rees and A.R. Young*

4.1 Introduction

The Himalayan region of Nepal and northern India experiences the full range of hydrological regimes, from extreme floods due to monsoonal rains to periods of very low flows during the dry-season. Approximately 80% of the annual rainfall occurs during the monsoon (Thapa, 1993) and, accordingly, the flood peaks during this period are very large compared to the dry-season flows. The average flows over the driest part of the year (December to February) are typically only 10-15% of the average flows during the wet period (July to September). While floods may cause an acute disaster, including the loss of human life, property and infrastructure, a lack of water during the dry-season has a chronic impact on the lives of local people. The majority of the population depends primarily on agriculture for a livelihood. Shortages of water during the dry-season affect the yield from crops and directly impact upon poverty in the region. There is little control over water use during the dry-seasons and, *ad hoc* diversions of river flow occur primarily for irrigation. Consequently, the competing demands for water are poorly managed.

The quantification of the natural availability of water within a catchment is integral to the effective management of water resources. In gauged catchments, where gauging stations exist and flow records are available, this assessment may be undertaken by analysing the observed hydrographs. Measures of the average volume of water available, at an annual and monthly resolution and estimates of the variability of flows, may be obtained directly from the observed data. However, there are many instances where water resources assessments are required for ungauged catchments where no observed data exists. Hence, there is a need to develop techniques for estimating flow statistics in ungauged catchments. This Chapter describes the development of a regional model to estimate dry-season flows in ungauged catchments, which will facilitate good water management practice in the region.

4.2 Study Area

The study focussed on an area spanning Nepal and the northern Indian state of Himachal Pradesh, both with similar topographic divisions along a north-south axis. As Figure 4.1 indicates, altitude increases significantly from south to north with low altitude plains (100-200m), followed by a series of “middle hills” or the Lesser Himalayas, then the High Himalaya to the north with altitudes in excess of 7000m. The relief has influenced the geomorphology of the region. Its steeply sloped areas are highly vulnerable to landslides and avalanches with intense weathering of rock slopes at higher elevations and subsequent deposition of sediment on high-angled scree slopes or as alluvial fans and valley fills.

The study area is affected by the monsoonal weather systems originating in the Bay of Bengal. A build up of heat over the land surface during the pre-monsoon period, beginning in April, creates areas of low pressure over northern India and the Himalayas. These are linked to colder air masses over the Indian Ocean and consequently feed moisture-rich air from the Bay of Bengal in a north westerly direction towards the areas of low pressure during the monsoon “wet” season. The north-westerly movement of the monsoon causes the summer rains to arrive first and most intensely in the eastern part of the HKH region. Local topographical features, however, such as the Mahabharat Range in Nepal, play an important role in controlling the movement of rain clouds from south to north, with most rainfall falling on the southerly slopes of these foothills. As a result, monsoon intensity decreases in a northerly direction, with the
southern lowlands generally receiving more monsoon rainfall than the mountain regions. This rain shadow effect occurs throughout the region, with the highest mountain ranges and the Tibetan Plateau to the north, receiving very little precipitation. Furthermore, the massive variations in topographic relief occurring over relatively short lateral distances result in a highly heterogeneous distribution of rainfall. The arrival of the monsoon in the far west of the region is also influenced by extra-tropical weather systems moving eastwards from the Mediterranean, which bring early pre-monsoon rains to the western portions of northern India as early as March (Singh et al., 1997).

**Figure 4.1** North-south variations in elevation (Source: Rees et al., 2001)

Differences in monsoonal hydrographs are illustrated in Figure 4.2. This compares the typical average annual hydrograph for a catchment in north western Indian (202020) with that from a catchment in eastern Nepal (106600). The relative intensity of the monsoon decreases from east to west across the HKH region. Singh et al. (1997) reported that 35-45% of the annual rainfall occurred during the monsoon season in the Chenab basin (Himachal Pradesh, while in Nepal the monsoon accounts for between 80-85% of the annual rainfall (Thapa, 1993).

**Figure 4.2** Typical average annual hydrographs from catchments in north western Indian (202020) and eastern Nepal (106600)
The storage of water as snow and ice plays an important role in the hydrology of the region. The seasonal snow line varies upwards from about 3000m, with permanent snow and ice occurring, typically, at elevations of 5000m and above. The relative contribution of melt-water to stream flow is greatest during the post monsoon period, gradually decreasing as temperatures fall to a minimum between December and January. A relatively high contribution from melt-water also occurs during the late spring (April to June) prior to the monsoon as temperatures begin to rise again after winter (Thapa, 1993). Table 4.1 summarises the regional climatic conditions.

**Table 4.1 Summary of climatic conditions in the HKH region**

<table>
<thead>
<tr>
<th>Season</th>
<th>Months</th>
<th>Source of rainfall</th>
<th>Rainfall</th>
<th>Snow and ice melt contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter</td>
<td>December to February/March</td>
<td>Late winter extra tropical weather systems of the mid latitudes that originate in the Caspian Sea and Mediterranean and move eastwards.</td>
<td>Relatively low in high mountains, and high in plains</td>
<td></td>
</tr>
<tr>
<td>Pre-monsoon</td>
<td>March/April to May/June</td>
<td>Light to moderate rain due to convective storms.</td>
<td>Relatively high in high mountains and low in plains</td>
<td>Increasing melt as temperatures rise</td>
</tr>
<tr>
<td>Monsoon</td>
<td>June/July to September</td>
<td>Heavy rain from monsoon, moist air currents from Bay of Bengal and Arabian sea, heaviest in the east.</td>
<td>High everywhere and higher in absolute terms on plains due to orographic effects. Southerly slopes receive more rainfall</td>
<td>Maximum from June/July to September/October</td>
</tr>
<tr>
<td>Post-monsoon</td>
<td>October to November</td>
<td>Little rainfall, dry in Himalayas and plains</td>
<td>Low</td>
<td>Amount of melt gradually decreases as the freezing level descends to lower elevations</td>
</tr>
</tbody>
</table>

4.3 Previous regionalisation studies

Regionalisation is a method for deriving quantitative relationships between hydrological behaviour and the physical and climatic characteristics of catchments in a given region. The process typically involves the definition of a region (geographically coherent or otherwise) in which models (or relationships) are developed by relating catchment characteristics to the hydrological variables of interest. In a water resources management context, these variables typically are flow duration statistics (assigning flows a probability of exceedence) and, in particular, the low flow part of the flow duration curve.

Within the HKH region, a number of studies have been made to develop models that predict aspects of the hydrological regime that are of interest to water resource managers, irrigation engineers, and hydropower engineers. The Water and Energy Commission Secretariat (WECS, 1990) produced the “WECS” method for estimating flow duration statistics in ungauged catchments, considering Nepal as one homogeneous region. Models for flow duration statistics
were linear regression-based using catchment area, catchment area above a certain elevation and a monsoon wetness-index (the net average rainfall between June and September) as dependent variables. The seasonal flow variations were described by linear regression-based models for long-term mean monthly flow, using the same dependent variables. Alford (1992) developed relationships between catchment annual specific discharge and catchment elevation in two regions (eastern and western) of Nepal. Braun et al. (1993) developed statistical relationships between runoff and glacial cover, for catchments in Nepal, enabling estimation of flows in ungauged catchments. Singh et al. (2001) developed regional flow duration curves for nine regions in the north-west (Indian) Himalayas. These curves were re-scaled by an estimate of mean flow based on catchment area. A regionalised flow estimation method was developed by Rees et al. (2002), which developed standardised flow duration curves based on catchment characteristics of geology and elevation. These were coupled with a water balance model for estimating runoff to estimate long-term flow duration curves for the purpose of assessing the potential of small hydropower schemes.

Many of the approaches to regionalisation of flow regimes in the HKH have focussed on flow duration statistics, as they enable the entire flow regime to be quantified. These statistics are useful for hydropower estimation methods, for example, where the area under the flow duration curve can be equated to a volume of water available to generate power from. However, from a water resources perspective, flows during the dry-season are the most important to predict, as this is when the competing demands for water are at a maximum. Furthermore, the timing of expected water availability is important to the cycle of crop growth and development. Analysis of dry-season flows separate from the entire hydrograph also reduces the impact of the high hydrometric uncertainties associated with observed high flows during the monsoon season. One hydrological analysis technique commonly used to analyse dry-season flow behaviour is recession curve analysis.

4.4 Recession curve analysis

The monsoonal nature of the flow regimes in the HKH, as illustrated in Figure 4.3, shows a regular period of recession following peak monsoon flows. During the HKH recession period, there is little or no rainfall and water gradually drains from the catchment via a complicated combination of soil and ground-water processes and evapotranspiration. These processes, particularly the drainage of an unsaturated soil layer, are very difficult to model and measure directly. The rate of decrease in flow is affected by factors including hydrogeology, soil types, topography, climate, catchment size and slope which all impact on the drainage process.

![Figure 4.3](image_url)  
**Figure 4.3** Hydrograph illustrating regular recession flows in a Nepalese catchment
Recession curve analysis has been used in the field of water resources management for many years. Boussinesq (1877) used recession curves to describe groundwater flow and, recently, Moore and Bell (2002) have used recession behaviour to model intermittent streamflow and the impacts of groundwater pumping in English chalk catchments. Hall (1968) defined baseflow and described baseflow recession behaviour. Recession analysis has also been used to define drainage parameters in hydrological models (Harlin, 1991). Tallaksen (1995) provides an excellent review of base-flow recession analysis. Recession analysis has also been used in the development of regional models predicting the low flow behaviour of rivers. Here, recession rates are used as a surrogate for catchment storage and hence are used to predict the degree to which a catchment can sustain flows during periods of no rainfall. In the HKH region, an example of the regionalisation of recession curve behaviour is presented by Delft Hydraulics (1995). A regional polynomial equation for predicting the slow-flow recession constant was developed based on catchment elevation, suggesting that steeper recessions were associated with catchments of high average elevation.

The suitability of recession curve analysis for defining dry-season flows in the HKH stems from the regular and uninterrupted nature of the recessions that occur in the region (Figure 4.3). The recession behaviour appears to be very predictable, with low year-to-year variability, and, hence, suggests that the average annual recession would provide a good measure of resource availability during the dry-season. The use of recession curves also removes the need to consider the hydrometric uncertainty associated with high flows recorded at gauging stations. During the wet season the measurement of flood flows will be uncertain reflecting insufficient ratings at high flows (due to practical difficulties of access and safety) or significant changes to measurement sections resulting from sedimentation or bank erosion during floods. However, it is normal hydrometric practice in the region for rating equations curves to be re-evaluated after each monsoon, when access to the site is good, and hence the accuracy of flow measurement during the subsequent dry-season should also be relatively good.

Development of a method for predicting long-term average recession curves for ungauged catchments in the HKH would enable the availability of water resources during the dry-season to be estimated. Critically, information regarding the temporal sequencing of flows is retained in a recession curve, hence allowing the water availability to be directly related to water requirements of, for example, a cropping calendar. Recession curve analysis has the added advantage of enabling dry-season conditions to be forecast from some flow measurements. When such models predicting natural availability are combined within the framework of an integrated water resources management (IWRM) tool, the impacts of water-use within a catchment can be simulated.

### 4.5 Mathematical formulation

The recession behaviour of a hydrograph can be described mathematically on the basis that the outflow from a conceptual catchment store is considered to be proportional to a power of the volume of water stored within the catchment,

\[ q = k S^m \quad k>0, \ m>0 \quad \text{Equation 1} \]

where \( q = q(t) \) is the outflow, \( k \) is the recession constant, \( S = S(t) \) is the storage, and \( m \) is the power term (\( m=1 \) for a linear store).

When this is combined with the continuity equation,

\[ \frac{dS}{dt} = u - q \quad \text{Equation 2} \]
where $u = u(t)$ is the input (i.e. effective rainfall) to the catchment store, then the general Horton-Izzard (Dooge, 1973) model describing the rate of change of flow from the catchment store can be derived as follows:

$$\frac{dq}{dt} = a(u-q)q^b$$  \hspace{1cm} \textit{Equation 3}

where $a = mk^{1/m}$ and $b = (m-1)/m$

\textit{Equation 3} can be solved exactly for any rational value of $m$ (Gill, 1976, 1977). Special cases exist where the inflow, $u$, is assumed to be zero and the solutions for the linear and non-linear cases are shown below, respectively;

$$q_{t+T} = \exp(-kT)q_t \quad (m = 1)$$  \hspace{1cm} \textit{Equation 4}

$$q_{t+T} = \left[ q_t^{-b} + a \cdot b \cdot T \right]^{-1/b} \quad (m \geq 2)$$  \hspace{1cm} \textit{Equation 5}

\textbf{4.6 Analysis of observed hydrographs}

There are two main traditional approaches to hydrograph analysis for the determination of an average recession curve constant, $k$: the matching strip method (Snyder, 1939); or the correlation method (Langbein, 1938). The correlation method is based on a linear storage model and involves plotting the flow at one time against the flow at some time “$n$” time periods later during known recession periods. The slope of an envelope line to these plots of individual recession curves can be identified at some point (the Institute of Hydrology (1980) suggest a flow value of one quarter of the mean daily flow). This slope then defines the recession constant (see Equation 6 below).

$$-k = \left[ q_{t+T} / q_t \right]^{1/T}$$  \hspace{1cm} \textit{Equation 6}

In the matching strip method, individual recessions are plotted and then adjusted temporally (i.e. along the ordinate axis) until the main recessions overlap to reflect the underlying “master” recession shape. An average line is drawn by eye through the data, from which a recession constant, $k$, may be determined. This process is based on the assumption of a linear storage model. Nathan and McMahon (1990) suggest that this approach is more accurate than the correlation method.

Both the correlation and matching strip methods are well suited to deriving the underlying recession behaviour from individual recession segments, which represent drainage from catchments stores with different initial storage conditions. However, in the case of monsoonal hydrographs, the storage at the beginning of the dry-season can be assumed to be fully saturated, hence initial storage conditions will be similar from year to year. Also both traditional techniques are restricted by the assumption of a linear storage model, which has not yet been determined to be appropriate for HKH catchments. Therefore, the following, alternative method for analysing recessions was developed:

1. First, recessions identified by the automated selection technique were reduced to an equal start date. This follows a similar logic to the matching strip method, but assumes that the initial storage conditions are the same.

2. Second, a linearised form of Equation 5 was developed and sets of points, representing each flow/time value, were plotted for each individual recession. A specific value of the storage model parameter $m$ ($m>2$) needed to be assumed.

3. Linear regression was then used to identify the recession constant, $k$, by fitting a line through the set of points for each recession curve and determining the gradient. This is
conceptually similar to the fitting a line “by eye” through points in the correlation method approach.

4.7 The catchment data set

A selection of gauged catchments from Nepal and Himachal Pradesh (India) were chosen to develop the regional recession model for the prediction of dry-season flows (see Table 4.2). The catchments were selected on the basis of good hydrometric quality and natural flow regimes. The data set included rain and snow-fed catchments located in the mid-elevation range of the Himalayas, see Figure 4.4.

Daily flow data from the Nepalese catchments were converted to the FAO 10-day format to be compatible with the Indian data and to provide a level of smoothing. Each hydrograph was visually examined as part of a detailed quality control process. Recession periods from catchment flow records were selected on the following basis: a recession was defined to begin at the third consecutively decreasing flow value; the recession was deemed to have ended at the first increasing flow value; and the minimum recession length was 100 days (i.e. ten 10-day flow values, to ensure that only the main annual recession was identified).

Figure 4.4 Location of the catchment data set

The impact of precipitation events during the recession periods was also examined to ascertain whether inputs, \( u(t) \), in Equation 3 could be assumed to be zero. This process was hampered by a lack of rainfall data for the Indian catchments and sparse and uncertain daily rainfall data in Nepal. A number of Nepalese stations were selected and an average precipitation time-series was developed from rain gauge records taken from the vicinity of the catchment. The average rainfall data was used to indicate whether or not rainfall occurred during recession periods. Hydrographs were compared to the “time-series” of rainfall and it was observed that rainfall
events tended either to be significant enough to signal the end of the recession period, or insufficient to impact on the observed shape of the recession curve. Similar observations had been made by Boorman et al. (1996) who were able to collect high resolution (30 minute) rainfall data. Hence, for the purpose of this recession curve analysis it was concluded that rainfall during recessions was minimal and the inputs in Equation 3 could, indeed, be assumed to be zero.

Table 4.2 Catchment data set of Nepalese and Indian catchments

<table>
<thead>
<tr>
<th>Station No.</th>
<th>River</th>
<th>Site</th>
<th>Area (km²)</th>
<th>Lat (°N)</th>
<th>Long (°E)</th>
<th>Years of data</th>
<th>Q95 (%MF)</th>
<th>AARD (mm)</th>
<th>Mean Elev (m)</th>
<th>Rainfall (mm/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>102250</td>
<td>Sinja Khola</td>
<td>Diware</td>
<td>764</td>
<td>29.32</td>
<td>81.92</td>
<td>18.0</td>
<td>10%</td>
<td>910</td>
<td>3416</td>
<td>792</td>
</tr>
<tr>
<td>102620</td>
<td>Thuli Gad</td>
<td>Khanayatal</td>
<td>886</td>
<td>28.94</td>
<td>80.97</td>
<td>17.0</td>
<td>5%</td>
<td>113</td>
<td>1443</td>
<td>1825</td>
</tr>
<tr>
<td>103300</td>
<td>Mari Khola</td>
<td>NayaGaon</td>
<td>1968</td>
<td>28.07</td>
<td>82.80</td>
<td>19.0</td>
<td>16%</td>
<td>915</td>
<td>1801</td>
<td>1763</td>
</tr>
<tr>
<td>103395</td>
<td>Jhimruk</td>
<td>Tigragaon</td>
<td>684</td>
<td>28.05</td>
<td>82.83</td>
<td>21.6</td>
<td>9%</td>
<td>1293</td>
<td>1662</td>
<td>1734</td>
</tr>
<tr>
<td>104150</td>
<td>Andhi Khola</td>
<td>Dumrichaur</td>
<td>480</td>
<td>27.97</td>
<td>83.59</td>
<td>20.0</td>
<td>8%</td>
<td>2115</td>
<td>1202</td>
<td>2498</td>
</tr>
<tr>
<td>104170</td>
<td>Badigad</td>
<td>Rudrabeni Gulmi</td>
<td>2002</td>
<td>27.97</td>
<td>83.47</td>
<td>18.3</td>
<td>5%</td>
<td>1783</td>
<td>1882</td>
<td>1926</td>
</tr>
<tr>
<td>104300</td>
<td>Seti</td>
<td>Phoolbari</td>
<td>573</td>
<td>28.23</td>
<td>80.92</td>
<td>15.2</td>
<td>16%</td>
<td>2901</td>
<td>2867</td>
<td>3424</td>
</tr>
<tr>
<td>104380</td>
<td>Madi Khola</td>
<td>ShishaGhat</td>
<td>887</td>
<td>28.10</td>
<td>82.83</td>
<td>14.2</td>
<td>17%</td>
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<td>15%</td>
<td>1430</td>
<td>1158</td>
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</tr>
<tr>
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<td>85.77</td>
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<td>Rajdwali</td>
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<td>Kankai Mai</td>
<td>Khola Mainachuli</td>
<td>1164</td>
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<td>87.88</td>
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<td>1632</td>
<td>1212</td>
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<td>Chirchind</td>
<td>75</td>
<td>32.45</td>
<td>76.42</td>
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<td>2792</td>
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<td>20%</td>
<td>3114</td>
<td>3573</td>
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<td>11.6</td>
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<td>2881</td>
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</tr>
<tr>
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<td>Soldan</td>
<td>93</td>
<td>31.57</td>
<td>77.92</td>
<td>15.0</td>
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<td>Brua</td>
<td>43</td>
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<td>Malana</td>
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<td>77.13</td>
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<td>19%</td>
<td>1941</td>
<td>3497</td>
<td>1517</td>
</tr>
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<td>77.13</td>
<td>15.8</td>
<td>19%</td>
<td>1396</td>
<td>3018</td>
<td>1471</td>
</tr>
</tbody>
</table>

Notes:
AARD (Average annual runoff depth (mm), the catchment mean flow expressed as an equivalent depth over the catchment area); Mean elevation (m a.s.l.) derived from a 1×1km digital elevation layer derived from the GTOPO data set (USGS, 1996); Mean annual rainfall, derived from gridded rainfall data sets 1×1km resolution (after Rees et al., 2002).

4.8 Defining the model form

The storage coefficient $m$ in Equation 1 dictates the conceptualisation of the drainage behaviour of the catchment store. Linear storage, represented by $m = 1$, has been shown to be theoretically applicable to modelling flows from confined or artesian aquifers (Werner and Sundquist, 1951; Ding, 1967). While the same authors show that the quadratic case, $m = 2$, represent flows from
unconfined aquifers. Horton (1938) concluded that the latter case was a reasonable choice for representing overland flow on natural surfaces, which could be extended to include flow from storage within a catchment.

The fit of the observed HKH flow data to a model form (defined by the $m$ value) was assessed by considering the average root mean squared standardised error (RMSSE) of predicted versus observed values over a number of individual recession periods. The standardised error removes the impact of recession scale, as it is only the recession shape that is important for determining an appropriate model form.

$$RMSSE = \sqrt{\frac{1}{n} \sum_{i=1}^{n} \left( \frac{X_i^{OBS} - X_i^{PRED}}{X_i^{OBS}} \right)^2}$$  \hspace{1cm} \text{Equation 7}

where $X_i^{OBS}$ and $X_i^{PRED}$ are the observed and predicted values in the $i^{th}$ catchment respectively.

The procedure detailed in Section 4.6, together with discrete values of $m$, was used to estimate the recession constant, $k$, for individual recessions. Predicted recession flow values were then calculated using the optimal value of $k$ and an assumed $m$. Hence, a RMSSE could be calculated by comparing observed and predicted flow values in each individual recession, enabling an average RMSSE to be calculated for each catchment. The average RMSSE indicates how appropriate the assumed model form ($m$ value) is for each catchment, with low values equating to better fits. The results, shown in Figure 4.5, show that the data from HKH catchments more closely follow a quadratic formulation than a linear one.

\[ q_{t+T} = \left[ q_t^b + a \cdot b \cdot T \right]^{-1/b} \hspace{1cm} \text{Equation 8}\]

where $a = m \cdot k^{1/m}$, $b = (m-1)/m$ and $m = 2$

Using this formulation it was possible to analyse observed recessions to determine the three parameters controlling the recession curve:
Recession constant (k); controls the rate of decrease of flows occurring during the recession. Large values of k are associated with steep recessions. Recession constants were derived for observed recessions using the procedure detailed in Section 4.6;

Initial flow (Qo); the flow at the beginning of the recession, in cumecs;

Recession start time (To); the start date for the recession, required to locate the recession within a calendar year.

The observed recession parameters determined using this methodology are shown on Table 4.3. These observed long-term average values of k, Qo, To were used to develop regionalised equations for predicting each parameter based on catchment characteristics. This would enable a recession curve to be developed for any ungauged catchment in the region.

4.9 Defining the recession constant, k

The recession constant k dictates the rate at which flows decrease during a recession period. This drainage response is a complex combination of water loss from the catchment; via evapotranspiration, groundwater flow, and surface water flow. Conceptually the recession behaviour of a catchment will depend on factors including catchment shape, size, topography, and primarily hydrogeology (e.g. Demuth and Schreiber, 1994). However, as noted by several authors, including Kinsel (1963), the relationship between recession behaviour and geological factors is complicated and will be influenced by site specific factors such as the depth of aquifer penetration, the orientation of groundwater storages relative to stream networks and the degree of fracture of confining material. Generally, slower recession rates could be expected from more permeable material that has a higher natural storage capacity. This has been observed in small Pre-Alp catchments by Pereira and Keller (1982).

The approach adopted in this study was to identify individual recessions from the time-series of flows recorded for a catchment and derive a recession constant for each recession. An average of these individual recession constants (AVE_k) was calculated to be the best long-term estimate of k for an individual catchment and the coefficient of variation (CV_k) reflects the variability of k. Recession constants for individual recessions were derived using a linearised form of Equation 8, as described in Section 4.6, and shown in Table 4.3.

The spatial trends in observed values of AVE_k showed k values increased in catchments to the north-west of the study area. However, closer examination revealed that this was a result of the fact that the selected Indian catchments were generally smaller than Nepalese catchments and the recession constant was highly correlated with catchment area. Within both countries AVE_k values appeared to vary by an order of magnitude.

4.9.1 Variability of observed recession constant

The observed variability of the recession constant is not just a function of catchment characteristics (e.g. size, shape and hydrogeology), but it is also related to evapotranspiration, as it too “removes” water from the catchment. Hence, if evapotranspiration varies considerably from year to year then it could be expected that the recession constants would also vary annually (Tallaksen, 1991). The variability of individually observed recession constants across the data set was examined to determine whether the range of k values could be drawn from the same population, with differences explained purely by sampling error. A matrix of t-tests was performed for each combination of catchments in the data set. The results showed that, at a 95% significance level, 73% of the combinations were significantly different and, at a 99% significance level, 59% of the combinations were significantly different. This strongly suggests that the values of observed recession constant were catchment dependent and are not derived from the same underlying population.
### Table 4.3 Observed average recession parameters for the catchment data set

<table>
<thead>
<tr>
<th>Station</th>
<th>AVE_k ($\times 10^8$)</th>
<th>CV_k</th>
<th>N</th>
<th>Average R² [1]</th>
<th>AVE_Qo</th>
<th>CV_Qo</th>
<th>N</th>
<th>AVE_To</th>
<th>AVE_To [2]</th>
<th>SD_To</th>
<th>N [4]</th>
</tr>
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<td>13</td>
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<td>0.47</td>
<td>14</td>
<td>22/Sep</td>
<td>266.36</td>
<td>20.0</td>
<td>14</td>
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<td>2127</td>
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<td>5</td>
<td>0.79</td>
<td>51.7</td>
<td>0.56</td>
<td>7</td>
<td>18/Sep</td>
<td>262.14</td>
<td>11.1</td>
<td>7</td>
</tr>
<tr>
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<td>202</td>
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<td>12</td>
<td>0.95</td>
<td>44.3</td>
<td>0.31</td>
<td>15</td>
<td>27/Sep</td>
<td>271.73</td>
<td>14.6</td>
<td>15</td>
</tr>
<tr>
<td>103395</td>
<td>581</td>
<td>0.41</td>
<td>14</td>
<td>0.93</td>
<td>54.4</td>
<td>0.42</td>
<td>16</td>
<td>28/Sep</td>
<td>272.63</td>
<td>16.4</td>
<td>16</td>
</tr>
<tr>
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<td>0.54</td>
<td>13</td>
<td>27/Sep</td>
<td>271.15</td>
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<td>5</td>
<td>0.95</td>
<td>89.7</td>
<td>0.34</td>
<td>7</td>
<td>16/Aug</td>
<td>229.86</td>
<td>11.6</td>
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<td>0.37</td>
<td>6</td>
<td>19/Aug</td>
<td>232.50</td>
<td>10.1</td>
<td>6</td>
</tr>
</tbody>
</table>

**Notes:**

[1] AVE R² is the average R² value of fitting the observed recessions to the assumed model form (m=2)
[2] AVE_Qo is expressed as an equivalent depth of water over the catchment area from a ten-day flow value
[3] AVE_To is expressed as number of days from January 1st
[4] N is the number of recessions used to estimate the average parameter value.

### 4.9.2 Sensitivity of OBS_AVE_k to the recessions selected

The sensitivity of the derived OBS_AVE_k values to the recession identification process was tested. The initial “n” flows (n = 1, 2 and 3) were removed from each individual recession and the OBS_AVE_k values re-derived. Likewise, the final “n” flows (n = 1, 2 and 3) were removed from each individual recession and the OBS_AVE_k values re-derived. The results indicated that the OBS_AVE_k value was robust with respect to the choice of recession period, with the adoption of Qo=QTo+1 resulting in changes of less than ±10% in all but four catchments.

### 4.9.3 Regionalisation of the recession constant

Spearman correlation analysis was used to identify relationships between the average recession constant (AVE_k) and catchment characteristics. Variables considered included scale, topography, climate and the fraction of frozen storage in the catchment. The result of the
correlation analysis is shown in Table 4.4. Spearman correlations minimise the impact of significant changes in the scale of the variables.

**Table 4.4 Correlations between catchment characteristics and AVE_k**

<table>
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<tr>
<th>Explanatory Variable</th>
<th>Spearman correlation coefficient with AVE_k</th>
</tr>
</thead>
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</tr>
<tr>
<td>MEAN_ELEV</td>
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</tr>
<tr>
<td>MEAN_ASP</td>
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</tr>
<tr>
<td>RANGE_AREA</td>
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</tr>
<tr>
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</tr>
<tr>
<td>F_GT_4500</td>
<td>-0.049</td>
</tr>
</tbody>
</table>

*Notes:*
- AREA – Catchment area in km²
- MEAN_ELEV - Mean elevation based on a 1km×1km elevation grid
- MEAN_ASP – Mean aspect, based on a derived 1×1km aspect grid of discrete values (360 = north, 180 = south)
- RANGE_AREA - Range of elevation in catchment per catchment area
- MEAN_RAIN – Catchment average annual rainfall mm
- F_GT_4500 - Fraction of the catchment above an assumed permanent snow line at 4500m

The significance of correlations between the dependent and explanatory variables were examined and inter-correlations between the explanatory variables were considered. These identified catchment area (AREA) as the best predictor variable. Linear regression analysis identified catchment 102620 as an outlier (standardised residual of 5.4) and examination of the individual recessions showed that the second order model may not be appropriate for this particular catchment. This confirms the high RMSSE found for 102620 in Section 4.8. With the removal of this outlier, the model was developed with a logarithmic transformation,

\[
AVE_k = 57544 \times AREA^{-0.793}
\]

*Equation 9*

where AVE_k is expressed in units of \(10^{-8}\), AREA in km².

The model fit (excluding 102620) was summarised by an \(R^2 \) value of 0.88, a factorial standard error (f.s.e.) of 1.45 and is illustrated in Figure 4.6. No significant relationships were found between catchment characteristics and the model residuals. Figure 4.6 also shows that the two smallest catchments in the data set, with the largest “k” values, depart most from the one-to-one relationship (205056 (43 km²); 206065 (36 km²)). The regression analysis did not identify these catchments as outliers or as exerting significant “leverage” on the model. It is possible that there are different controls on the recession behaviour in these very small catchments, for example, local geological conditions or possible artificial controls on the flow regime. The equation suggests that as catchment area increases the storage coefficient decreases, indicating that water is lost more slowly from catchment storages. This suggests that increasing catchment size results in a “dampening” of the recession response.
4.9.4 Impact of catchment permeability on the recession constant

Conceptually, a relationship between catchment permeability and the recession constant would be expected. However, it was not possible to identify such a relationship using the data sets available for this study. A further detailed investigation of such a relationship was made using an expanded data set of 28 Nepalese catchments (the calibration and evaluation data set, see Section 4.12). The geological spatial data set used for this investigation was the 1:1,000,000 Scale Geological Map of Nepal (after Rees et al., 2001). It was found that the value of OBS_AVE_k for catchments with very similar distributions of geological classes was still controlled by catchment area and when catchments of similar size, but different geology, were considered, the variation of the observed recession constant was relatively low. No significant correlations could be found between catchment size and fractional extents of geological classes. Hence, catchment area (in Equation 9) is unlikely to be acting as a surrogate for permeability. Regressions of the residual variance of the catchment area model against the fractional extents of geological classes did not identify catchment permeability as a significant influence. It is likely that this lack of influence is a reflection of the scale at which the geological classes are mapped, for example, drift geology types are not represented. Hence, on the basis of the data available, the model including only catchment area was reaffirmed as the most appropriate for estimating AVE_k.

4.10 Estimating the initial recession flow, Qo

The flow at the start of a recession period reflects the initial volume of water available in storage. Individual recessions for the test catchments were examined to derive an initial flow for each recession. The impact of scale was removed by expressing the Qo flows as an equivalent depth of water over the catchment. Average values of Qo (AVE_Qo) for the catchments are shown in Table 4.3, together with the coefficient of variation of the Qo values (CV_Qo).

The variability of the average initial recession flow was examined, considering all individual Qo values, to determine whether the range of observed Qo values could be drawn from the same population, with differences explained purely by sampling error. A matrix of t-tests was performed for each combination of catchments in the data set. The results showed that, at a 95% significance level, 50% of the combinations were significantly different and, at a 99% significance level, 35% of the combinations were significantly different. These results suggest that the values of observed initial recession flows were catchment dependent and are not derived from the same underlying population.
### 4.10.1 Regionalisation of the initial recession flow

A strong relationship was found between observed average annual runoff depth (AARD), that is, catchment mean flow expressed as an equivalent depth, and AVE_Qo. This indicated that catchments having larger runoff on an annual basis, also normally experience higher initial recession flows during recession periods (see Figure 4.7). This probably reflects the fact that AARD is heavily influenced by the flows occurring during the monsoon period, and that the initial flow of the recession is effectively the last flow of the monsoon period.

![Graph showing the relationship between AARD and AVE_Qo](image)

**Figure 4.7** Average recession flow (AVE_Qo) vs average annual runoff depth (AARD)

Although this observed relationship could not be exploited directly for the purpose of estimating AVE_Qo in ungauged catchments (since no value of AARD will exist in the absence of flow records), it is useful for focussing the selection of potential regionalisation catchment characteristics. Spearman correlations between AVE_Qo and catchment characteristics were examined with the most significantly correlated variables shown in Table 4.5. The table also quantifies the correlation between AVE_Qo and the observed AARD to be 0.91.

<table>
<thead>
<tr>
<th>Explanatory Variable</th>
<th>Spearman correlation coefficient with AVE_Qo (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AARD_OBS</td>
<td>0.913</td>
</tr>
<tr>
<td>MEAN_ELEV</td>
<td>0.454</td>
</tr>
<tr>
<td>MAX_ELEV</td>
<td>0.703</td>
</tr>
<tr>
<td>CV_ELEV</td>
<td>0.191</td>
</tr>
<tr>
<td>RANGE_AREA</td>
<td>0.554</td>
</tr>
<tr>
<td>MEAN.asp</td>
<td>0.134</td>
</tr>
<tr>
<td>MEAN_RAIN</td>
<td>0.084</td>
</tr>
</tbody>
</table>

**Notes:**
- AARD_OBS – Observed average annual runoff depth, mean flow expressed as an equivalent depth over the catchment
- MAX_ELEV – The maximum elevation occurring in the catchment based on 1×1km elevation grid
- CV_ELEV – Coefficient of variation of elevation (standard deviation / mean) based on 1×1km elevation grid
- MEAN.asp – Mean aspect, based on a derived 1×1km aspect grid of discrete values (360 = north, 180 = south)
- RANGE_AREA – difference between catchment maximum and minimum elevations, based on 1×1km elevation grid, divided by the catchment area
During the analysis, station 106500 was found to be an outlier in the data set. This catchment has a much higher than expected value of AVE_Qo and the recessions begin early, when compared to neighbouring stations (such as 106600) and Nepalese stations generally. Station 106500 has almost twice the observed value of AARD (4173 mm) of the neighbouring 106600 (2128 mm) although the spatial patterns of annual and monsoonal rainfall for the two catchments are very similar. Examination of the flow record for this station showed it to be inconsistent compared with neighbouring stations with respect to initial recession flow conditions and hence this station was excluded from the data set for this analysis.

The relationship between MAX_ELEV and AVE_Qo was explored by considering the fraction of a catchment area located above the permanent snow line, approximately 4500 m, using the F_GT_4500 variable. However this variable was not found to be useful for explaining the observed variance of AVE_Qo and was inter-correlated with MEAN_ELEV.

The significance of correlations between the dependent and explanatory variables was examined and inter-correlations between the explanatory variables were considered. This identified topographic variables as the best explanatory variables, and reflects the relationship between rainfall, runoff and elevation existing in the highly mountainous HKH region. However, the very weak relationships obtained between AVE_Qo, probably reflect the inadequacy of the existing rain-gauge network to represent rainfall distribution in the region. Consequently, it appears that in the Qo model elevation measures are acting as surrogates for rainfall.

The final model for estimating AVE_Qo is shown below in Equation 10. Checks were made to ensure that significant collinearity did not exist between CV_ELEV and MEAN_ELEV and that the coefficients obtained were significantly different from zero.

\[
AVE_Qo = 128.743 \times CV_ELEV + 0.0215 \times MEAN_ELEV - 4.393
\]

Equation 10

CV_ELEV is the coefficient of variation of elevation within the catchment (from a 1km elevation grid) and MEAN_ELEV is the average elevation for the catchment, derived from the same 1 km elevation grid.

An examination of residuals for this model showed that no significant relationships existed between the residuals and catchment characteristics. The performance of this model was moderately good, as indicated by a R² value of 0.41 and a standard error of 27.6 mm (excluding 106500). A linear regression using a logarithmic transformation was applied to calculate a factorial standard error (f.s.e.) for this model of 1.40 (excluding 106500). Figure 4.8 illustrates the relationship between the predicted and observed values of Qo.

The formulation of this equation suggests that higher elevation catchments experience higher initial recession flows as do catchments with greater variation of relief, which reflects the observed relationships between AARD and elevation within the data set.

Possible relationships between AVE_Qo and rainfall were examined by considering only Nepalese catchments, as more reliable average annual rainfall data was available for Nepal. This analysis showed that models for estimating AVE_Qo could be improved by use of more accurate rainfall data.
4.10.2 Sensitivity of the Qo relationship
The estimation of Qo for individual recessions is obviously dependant on the criteria used to define the start of the recession period. Uncertainties associated with the flow data, especially during the monsoon period, prevented a more rigorous method for defining the start of recession to be developed. Tests were conducted to examine the impact of choosing different initial recession flows on the correlations between the assumed initial flow and catchment characteristics. The changes to the correlation coefficients were shown to be small (less than 0.1) which confirms that the relationships between controlling factors and initial recession flows are robust with respect to the choice of initial recession flow, and, therefore, the simple method for defining the start of a recession is appropriate.

4.11 Timing the start of recession, To
The start dates (To) for recessions were examined to enable the recession period to be fixed within a calendar year. The start date for each individual recession was taken as the date corresponding to the initial recession flow, Qo. An average start date (AVE_To) was determined by averaging the start date (the number of days from the 1 January) for each recession (see Table 4.3).

The calculations show that recessions tend to start later in Nepalese catchments than in Indian catchments, an effect that had also been observed by Chalise (1996). A t-test was used to show that the difference in average start dates between Indian and Nepalese catchments was significant at the 95% confidence level.

Once the difference between the start dates for recessions in Nepal and India had been shown to be significant, the individual To values from both areas were examined to determine whether the range of observed To values could be drawn from the same population, with differences explained purely by sampling error. A matrix of t-tests was performed for each combination of catchments in the data set. The results showed that, at a 95% significance level, 40% of the combinations were significantly different and, at a 99% significance level, 27% of the combinations were significantly different. This weakly suggests that the values of observed recession start dates are catchment dependent and are not derived from the same underlying population. This result is not surprising given that the variability of the AVE_To across all catchments was not high (standard deviation of 17 days).
4.11.1 Regionalisation of the start date for recessions

As the monsoon weather system moves from east to west, it reduces in intensity. The consequence of this is that the monsoon season is shorter in the west of the HKH region than in the east (Chalise, 1996). Hence, the recessions tend to begin earlier in the west of the region, as reflected in the catchment data set. This relationship between geographical location and the timing of the beginning of the recession focussed the regionalisation study on location variables, see Table 4.6. Elevation variables are also shown as they reflect location in a north-south direction.

Table 4.6 Correlation between catchment characteristics and AVE_To

<table>
<thead>
<tr>
<th>Explanatory Variable</th>
<th>Spearman correlation coefficient with AVE_To (day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LAT_CENT</td>
<td>-0.714</td>
</tr>
<tr>
<td>LNG_CENT</td>
<td>0.663</td>
</tr>
<tr>
<td>DIST</td>
<td>-0.659</td>
</tr>
<tr>
<td>MEAN_ELEV</td>
<td>-0.769</td>
</tr>
<tr>
<td>MIN_ELEV</td>
<td>-0.689</td>
</tr>
<tr>
<td>MAX_ELEV</td>
<td>-0.522</td>
</tr>
<tr>
<td>SD_ELEV</td>
<td>-0.355</td>
</tr>
<tr>
<td>RANGE_AREA</td>
<td>-0.730</td>
</tr>
</tbody>
</table>

The results show strong correlations between the timing of the recession with catchment latitude and longitude. Hence, the inter-correlation between the co-ordinates of the catchment centroid (LONG_CENT and LAT_CENT) were resolved by developing the DIST measure, which is the straight line distance from the catchment centroid (measured in degrees) to an arbitrary origin at (90.0°, 25.3°). The arbitrary origin is located south east of Nepal’s eastern boundary, hence DIST reflects the proximity of the catchment to the Bay of Bengal, from which the monsoonal weather patterns originate,

\[ DIST = \sqrt{(\text{LONG}_\text{CENT} - 90.0)^2 + (\text{LAT}_\text{CENT} - 25.3)^2} \]  

where LONG_CENT and LAT_CENT are the co-ordinates of the catchment centroid in decimal degrees latitude and longitude respectively.

The relationship between start date and the mean elevation (MEAN_ELEV) variable may reflect the weakening of the monsoon in the south to north direction noted by Kansakar et al. (2002), which would correspond to recessions beginning earlier in the northern higher elevation catchments.

The significance of correlations between the dependent and explanatory variables was examined and inter-correlations between the explanatory variables were considered, to finally identify DIST and MEAN_ELEV as the best explanatory variables. Collinearity checks were performed for these two variables and both regression coefficients were found to be significantly different from zero. The model for AVE_To, the average start date of a recession, expressed as the number of days from January 1st, can thus be written,

\[ AVE_{-To} = 291.031 - 2.044 \times DIST - 0.0076 \times MEAN_{-ELEV} \]
where DIST is the distance (degrees decimal) from an arbitrary origin at (90.0°, 25.3°), and MEAN_ELEV is the mean elevation of the catchment (meters above sea level) obtained using 1km resolution digital elevation data.

The model structure suggests that the recessions begin earlier the further away from the Bay of Bengal the catchment is located, and also begin earlier in higher elevation catchments. Performance of the AVE_To model was good, as indicated by a $R^2$ value of 0.61 and a standard error of 10.8 days, which is less than the standard deviation of the observed To values for all but one catchment. A linear regression using a logarithmic transformation was applied to calculate a factorial standard error (f.s.e.) for this model of 1.04. Figure 4.9 shows the relationship between the predicted and observed values of AVE_To.

![Figure 4.9 Comparison of predicted and observed values of AVE_To](image)

**Figure 4.9** Comparison of predicted and observed values of AVE_To

### 4.12 Evaluation of the regional models

An evaluation data set was prepared to test the robustness of the models developed to estimate the recession constant, k, the initial flow, Qo, and the start date of the recession, To. The catchments included in this evaluation data set (see Table 4.7) were those remaining available catchments of good hydrometric quality, having more than ten years of flow records. None of the Indian catchments with data available satisfied these simple criteria.

The recessions of the evaluation data set were analysed using the methodology developed previously to determine observed average values of k, Qo and To. These were compared to the recession parameters predicted using the regional models. The results for the recession constant, “k” are shown in Table 4.8 and Figure 4.10.
### Table 4.7 Evaluation data set

<table>
<thead>
<tr>
<th>Stn</th>
<th>RIVER SITE</th>
<th>AREA (km²)</th>
<th>LAT</th>
<th>LNG</th>
<th>Years' flow data</th>
<th>Q95 (%MF)</th>
<th>AARD (mm)</th>
<th>Mean Elev (m)</th>
<th>Mean Rain (mm/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>101200</td>
<td>Chamelia Karkale Gaon</td>
<td>1279</td>
<td>29.67</td>
<td>80.56</td>
<td>22</td>
<td>23%</td>
<td>1355</td>
<td>3181</td>
<td>2422</td>
</tr>
<tr>
<td>102200</td>
<td>Tila Nala Nagma</td>
<td>1786</td>
<td>29.32</td>
<td>81.92</td>
<td>19</td>
<td>20%</td>
<td>824</td>
<td>3586</td>
<td>1243</td>
</tr>
<tr>
<td>104280</td>
<td>Mardi Lahachok</td>
<td>137</td>
<td>28.31</td>
<td>84.35</td>
<td>19</td>
<td>12%</td>
<td>4023</td>
<td>2358</td>
<td>4168</td>
</tr>
<tr>
<td>104393</td>
<td>Khudi Khudi Bazar</td>
<td>136</td>
<td>28.29</td>
<td>84.36</td>
<td>11</td>
<td>19%</td>
<td>2542</td>
<td>2559</td>
<td>3056</td>
</tr>
<tr>
<td>104400</td>
<td>Chepe GaramBesi</td>
<td>307</td>
<td>28.06</td>
<td>84.49</td>
<td>23</td>
<td>15%</td>
<td>2303</td>
<td>1803</td>
<td>2851</td>
</tr>
<tr>
<td>104468</td>
<td>Phalankhu Betrawati</td>
<td>147</td>
<td>27.97</td>
<td>85.19</td>
<td>17</td>
<td>9%</td>
<td>2955</td>
<td>2142</td>
<td>2474</td>
</tr>
<tr>
<td>104480</td>
<td>Tadi Belkot</td>
<td>651</td>
<td>27.86</td>
<td>85.14</td>
<td>25</td>
<td>10%</td>
<td>1960</td>
<td>1630</td>
<td>2496</td>
</tr>
<tr>
<td>104700</td>
<td>Lothar Lothar</td>
<td>167</td>
<td>27.25</td>
<td>84.72</td>
<td>25</td>
<td>12%</td>
<td>1673</td>
<td>988</td>
<td>2000</td>
</tr>
<tr>
<td>105050</td>
<td>Bagmati Sundarijal</td>
<td>16</td>
<td>27.71</td>
<td>85.46</td>
<td>25</td>
<td>13%</td>
<td>2063</td>
<td>2023</td>
<td>2417</td>
</tr>
<tr>
<td>105362</td>
<td>Bishnumati Budhanilkantha</td>
<td>6</td>
<td>27.78</td>
<td>85.36</td>
<td>22</td>
<td>7%</td>
<td>1516</td>
<td>1874</td>
<td>2417</td>
</tr>
<tr>
<td>105400</td>
<td>Nakhu Tika Bhairab</td>
<td>42</td>
<td>27.58</td>
<td>85.31</td>
<td>15</td>
<td>6%</td>
<td>868</td>
<td>1772</td>
<td>1779</td>
</tr>
<tr>
<td>105500</td>
<td>Bagmati Chovar</td>
<td>587</td>
<td>27.66</td>
<td>85.30</td>
<td>11</td>
<td>3%</td>
<td>932</td>
<td>1531</td>
<td>1804</td>
</tr>
<tr>
<td>105890</td>
<td>Bagmati PandheraDovan</td>
<td>2806</td>
<td>27.11</td>
<td>85.45</td>
<td>16</td>
<td>6%</td>
<td>1652</td>
<td>1066</td>
<td>2076</td>
</tr>
<tr>
<td>106400</td>
<td>Roshi Panauti</td>
<td>85</td>
<td>27.58</td>
<td>85.51</td>
<td>17</td>
<td>20%</td>
<td>1109</td>
<td>1899</td>
<td>1816</td>
</tr>
</tbody>
</table>

### Table 4.8 Performance of model for recession constant, k, with the evaluation data set

<table>
<thead>
<tr>
<th>Stn</th>
<th>AREA (km²)</th>
<th>OBS_AVE_k (x10⁸)</th>
<th>CV_k</th>
<th>Number of recessions</th>
<th>PRED_AVE_k</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>101200</td>
<td>1279</td>
<td>125.5</td>
<td>0.15</td>
<td>6</td>
<td>197.8</td>
<td></td>
</tr>
<tr>
<td>102200</td>
<td>1786</td>
<td>122.0</td>
<td>0.24</td>
<td>15</td>
<td>151.8</td>
<td></td>
</tr>
<tr>
<td>104280</td>
<td>137</td>
<td>1203.1</td>
<td>0.31</td>
<td>6</td>
<td>1166.2</td>
<td></td>
</tr>
<tr>
<td>104393</td>
<td>136</td>
<td>302.2</td>
<td>0.46</td>
<td>5</td>
<td>1168.3</td>
<td>Unusually low OBS_AVE_k value</td>
</tr>
<tr>
<td>104400</td>
<td>307</td>
<td>555.3</td>
<td>0.36</td>
<td>14</td>
<td>613.0</td>
<td></td>
</tr>
<tr>
<td>104468</td>
<td>147</td>
<td>1754.6</td>
<td>0.29</td>
<td>12</td>
<td>1101.9</td>
<td></td>
</tr>
<tr>
<td>104480</td>
<td>651</td>
<td>408.7</td>
<td>0.19</td>
<td>11</td>
<td>337.9</td>
<td></td>
</tr>
<tr>
<td>104700</td>
<td>167</td>
<td>2259.2</td>
<td>0.23</td>
<td>6</td>
<td>991.9</td>
<td></td>
</tr>
<tr>
<td>105050</td>
<td>16</td>
<td>10486.5</td>
<td>0.30</td>
<td>12</td>
<td>6426.0</td>
<td>Outside range of AREA in calibration data set</td>
</tr>
<tr>
<td>105362</td>
<td>6</td>
<td>80511.9</td>
<td>0.36</td>
<td>5</td>
<td>13505.9</td>
<td>Outside range of AREA in calibration data set</td>
</tr>
<tr>
<td>105400</td>
<td>42</td>
<td>30126.4</td>
<td>0.27</td>
<td>3</td>
<td>2968.4</td>
<td>At minimum of range of AREA in calibration data set plus poor hydrometry</td>
</tr>
<tr>
<td>105500</td>
<td>587</td>
<td>2169.9</td>
<td>0.36</td>
<td>5</td>
<td>366.7</td>
<td></td>
</tr>
<tr>
<td>105890</td>
<td>2806</td>
<td>251.9</td>
<td>0.47</td>
<td>8</td>
<td>106.1</td>
<td></td>
</tr>
<tr>
<td>106400</td>
<td>85</td>
<td>1994.8</td>
<td>0.59</td>
<td>6</td>
<td>1699.7</td>
<td></td>
</tr>
</tbody>
</table>

The performance against the evaluation data set (excluding those outside the range of the calibration data set) appears to be good. An overall average bias (the difference between observed and predicted is expressed as a percentage of the observed) has a value of +13% and a root mean square error of 1365 for the evaluation data set, compared with values of –6% and 802 for the original calibration data set.
Analysis of the initial recession flows, $Q_0$, made use of a sub-set of the recessions used in the analysis for the recession constant. The observed average initial recession flows, expressed as an equivalent depth, are shown on Table 4.9 and are compared to the values predicted by the regional model in Figure 4.11.

**Table 4.9 Performance of model for initial recession flow, $Q_0$, with evaluation data set**

<table>
<thead>
<tr>
<th>Stn</th>
<th>MEAN_ELEV (m a.s.l.)</th>
<th>CV_ELEV</th>
<th>OBS_AVE_Qo (mm)</th>
<th>CV_Qo</th>
<th>Number of recessions</th>
<th>PRED_AVE_Qo (mm)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>101200</td>
<td>3180.8</td>
<td>0.41</td>
<td>49.7</td>
<td>0.18</td>
<td>8</td>
<td>116.5</td>
<td></td>
</tr>
<tr>
<td>102200</td>
<td>3586.2</td>
<td>0.20</td>
<td>43.5</td>
<td>0.28</td>
<td>13</td>
<td>98.9</td>
<td></td>
</tr>
<tr>
<td>104280</td>
<td>2357.8</td>
<td>0.35</td>
<td>233.5</td>
<td>0.17</td>
<td>7</td>
<td>91.2</td>
<td></td>
</tr>
<tr>
<td>104393</td>
<td>2558.5</td>
<td>0.36</td>
<td>80.1</td>
<td>0.18</td>
<td>4</td>
<td>96.6</td>
<td>Suspect AARD</td>
</tr>
<tr>
<td>104400</td>
<td>1802.9</td>
<td>0.51</td>
<td>106.8</td>
<td>0.25</td>
<td>12</td>
<td>100.5</td>
<td></td>
</tr>
<tr>
<td>104468</td>
<td>2142.0</td>
<td>0.40</td>
<td>152.9</td>
<td>0.19</td>
<td>9</td>
<td>93.2</td>
<td></td>
</tr>
<tr>
<td>104480</td>
<td>1630.2</td>
<td>0.49</td>
<td>78.5</td>
<td>0.26</td>
<td>10</td>
<td>94.1</td>
<td></td>
</tr>
<tr>
<td>104700</td>
<td>988.4</td>
<td>0.34</td>
<td>55.4</td>
<td>0.27</td>
<td>5</td>
<td>60.6</td>
<td></td>
</tr>
<tr>
<td>105050</td>
<td>2022.6</td>
<td>0.10</td>
<td>90.5</td>
<td>0.22</td>
<td>8</td>
<td>52.0</td>
<td></td>
</tr>
<tr>
<td>105362</td>
<td>1873.6</td>
<td>0.13</td>
<td>78.0</td>
<td>0.17</td>
<td>6</td>
<td>52.0</td>
<td></td>
</tr>
<tr>
<td>105400</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>No data suitable</td>
</tr>
<tr>
<td>105500</td>
<td>1531.1</td>
<td>0.16</td>
<td>28.7</td>
<td>0.15</td>
<td>5</td>
<td>49.6</td>
<td></td>
</tr>
<tr>
<td>105890</td>
<td>1066.2</td>
<td>0.58</td>
<td>45.4</td>
<td>0.17</td>
<td>8</td>
<td>92.9</td>
<td></td>
</tr>
<tr>
<td>106400</td>
<td>1899.4</td>
<td>0.14</td>
<td>53.8</td>
<td>0.17</td>
<td>4</td>
<td>54.7</td>
<td></td>
</tr>
</tbody>
</table>
Again, the performance of the model for initial recession flow over the evaluation data set is good. An overall average bias value of –31% and a root mean square error of 37 for the evaluation data set (excluding 104280), compared with values of –16% and 28 for the calibration data set (excluding 106500).

The performance of the model for estimating the average start date of the recession was similarly tested over the evaluation data set, using the same recessions used in the Qo analysis. The observed To values are shown in Table 4.10.

Table 4.10 Performance of model for start date of recession, To, with evaluation data set

<table>
<thead>
<tr>
<th>Stn</th>
<th>MEAN_ELEV (m a.s.l.)</th>
<th>DIST</th>
<th>OBS_AVE_To (days from 1 Jan)</th>
<th>SD_To</th>
<th>Number of recessions</th>
<th>PRED_AVE_To</th>
</tr>
</thead>
<tbody>
<tr>
<td>101200</td>
<td>3180.8</td>
<td>10.222</td>
<td>275.0</td>
<td>16.9</td>
<td>8</td>
<td>246.1</td>
</tr>
<tr>
<td>102200</td>
<td>3586.2</td>
<td>8.669</td>
<td>265.1</td>
<td>13.8</td>
<td>13</td>
<td>246.2</td>
</tr>
<tr>
<td>104280</td>
<td>2357.8</td>
<td>6.841</td>
<td>259.3</td>
<td>9.8</td>
<td>7</td>
<td>259.2</td>
</tr>
<tr>
<td>104393</td>
<td>2558.5</td>
<td>6.459</td>
<td>290.5</td>
<td>19.7</td>
<td>4</td>
<td>258.5</td>
</tr>
<tr>
<td>104400</td>
<td>1802.9</td>
<td>6.127</td>
<td>265.0</td>
<td>8.5</td>
<td>12</td>
<td>264.9</td>
</tr>
<tr>
<td>104468</td>
<td>2142.0</td>
<td>5.435</td>
<td>263.9</td>
<td>10.5</td>
<td>9</td>
<td>263.8</td>
</tr>
<tr>
<td>104480</td>
<td>1630.2</td>
<td>5.342</td>
<td>271.0</td>
<td>14.3</td>
<td>10</td>
<td>267.8</td>
</tr>
<tr>
<td>104700</td>
<td>988.4</td>
<td>5.752</td>
<td>265.0</td>
<td>7.1</td>
<td>5</td>
<td>271.8</td>
</tr>
<tr>
<td>105050</td>
<td>2022.6</td>
<td>5.219</td>
<td>268.8</td>
<td>11.9</td>
<td>8</td>
<td>265.1</td>
</tr>
<tr>
<td>105362</td>
<td>1873.6</td>
<td>5.269</td>
<td>270.0</td>
<td>10.5</td>
<td>6</td>
<td>266.1</td>
</tr>
<tr>
<td>105500</td>
<td>1531.1</td>
<td>5.216</td>
<td>277.0</td>
<td>14.8</td>
<td>5</td>
<td>268.8</td>
</tr>
<tr>
<td>105890</td>
<td>1066.2</td>
<td>4.921</td>
<td>280.1</td>
<td>15.4</td>
<td>8</td>
<td>272.9</td>
</tr>
<tr>
<td>106400</td>
<td>1899.4</td>
<td>5.089</td>
<td>280.0</td>
<td>12.9</td>
<td>4</td>
<td>266.3</td>
</tr>
</tbody>
</table>
Given the observed variability in the calibration data set, the performance of the model for recession start date over the evaluation data set was considered to be good. An overall average bias value of +3% and a root mean square error of 12 for the evaluation data set compares very well with values of +2% and 11 for the calibration data set. Figure 4.12 compares the performance between the calibration and evaluation data sets.

![Figure 4.12](image)

**Figure 4.12 Performance of model start date of recession, To with evaluation data set**

Once the evaluation of the regional models was completed, the evaluation data set was combined with the calibration data set and the regional model coefficients, \( k \), \( Q_0 \) and \( T_0 \), re-evaluated. This was undertaken to make use of all available good quality data and maximise the sampling of data points in this data sparse region. The final models are shown below:

\[
\text{AVE}_k = 70170 \times \text{AREA}^{-0.817} 
\]

*Equation 13*

where \( n = 35 \) (105362, 105400, 105500, 104393 and 102620 omitted); \( R^2 = 0.88; \) f.s.e. = 1.49

\[
\text{AVE}_Q_0 = 89.173 \times \text{CV}_\text{ELEV} + 0.0193 \times \text{MEAN}_\text{ELEV} + 8.582 
\]

*Equation 14*

\( n = 37 \) (105400, 106500 and 104280 omitted); \( R^2 = 0.23; \) f.s.e = 1.47

\[
\text{AVE}_T_0 = 291.135 - 2.274 \times \text{DIST} - 0.0044 \times \text{MEAN}_\text{ELEV} 
\]

*Equation 15*

\( n = 37 \) (105400, 106500 and 104393 omitted); \( R^2 = 0.65; \) f.s.e. = 1.04

The relatively poor fit (described by the \( R^2 \) value) of the AVE\(_Q_0\) model was investigated. It was found that the performance of the new model compared well with the “calibration” model. The bias and root mean square errors of the calibration model and new model were found to be -0.17 and 30.0 and -0.12 and 29.0, respectively. It was concluded that the reduction in the \( R^2 \) statistic was a result of the small sample sizes in both the calibration and full data sets.
4.13 Performance of the regional models

Measures were identified to assess the performance of the regional models by comparing the observed average annual recession curve against the predicted average annual recession curve. The first, the Standardised Root Mean Square Error (SRMSE) is a standardised measure of random error and was calculated as the root mean square error of flows between 1 October and 1 February, standardised by the observed average flow over the same period.

\[
SRMSE = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (Q_{OBS}^i - Q_{PRED}^i)^2}
\]

Equation 16

where \(Q_{OBS}^i\) and \(Q_{PRED}^i\) are the observed and predicted 10-day flow value at time “i” in \(m^3/s\), respectively between 1 October and 1 February (n = 13).

The second measure, \(BIAS_{VOL}\), is a measure of the model’s ability to replicate the volume of water passing through the catchment during a recession. The measure is particularly important from a water resource management perspective, where the volumetric water requirements during recession periods must be compared with the natural supply. \(BIAS_{VOL}\) is calculated as the difference between the area under the observed and predicted recession curves, expressed as a fraction of the area under the observed recession:

\[
BIAS_{VOL} = \frac{\sum_{i=1}^{n} (Q_{OBS}^i - Q_{PRED}^i)}{\sum_{i=1}^{n} Q_{OBS}^i}
\]

Equation 17

The difference in volume of observed and predicted water passing through the catchment in the recession period can also be expressed as an equivalent depth (in mm) of water over the catchment area. This produces the third performance measure, \(ERR_{DEPTH}\) that is independent of catchment size:

\[
ERR_{DEPTH} = \frac{3600 \times 24 \times 10 \times \sum_{i=1}^{n} (Q_{OBS}^i - Q_{PRED}^i)}{(1000 \times A)}
\]

Equation 18

where \(ERR_{DEPTH}\) is the difference in volume of the recession curve (between 1 October and 1 February) expressed as an equivalent depth over the catchment area (A) in \(km^2\).

The revised regional models developed in Section 4.12 were used to predict recession curves for all 39 of the available catchments (i.e. the 26 calibration catchment plus the 14 evaluation catchments but excluding 105400) and the above performance measures calculated accordingly. The results in Table 4.11 show that the performance of the regional model, for estimating long-term annual recessions, was very good. The average \(ERR_{DEPTH}\) in absolute terms was 90mm for Nepalese catchments and 83mm for Indian catchments, and therefore the models performed equally well across the region. Of the 39 catchments, the \(BIAS_{VOL}\) was within \(\pm 25\%\) for 22 catchments (i.e. 64\% of the data set), and 32 of the 39 catchments had \(BIAS_{VOL}\) values within \(\pm 50\%\). The prediction of the mid-January flow (Jan 11th) was within \(\pm 50\%\) for 32 of the 39 catchments.
Table 4.11 Average performance measures across the data set

<table>
<thead>
<tr>
<th>Performance Measure</th>
<th>Average</th>
<th>Standard Deviation</th>
<th>Number of catchments within ± SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>BIASVOL</td>
<td>-0.13</td>
<td>0.47</td>
<td>31</td>
</tr>
<tr>
<td>ERRDEPTH</td>
<td>5.74</td>
<td>110.50</td>
<td>27</td>
</tr>
<tr>
<td>SRMSE</td>
<td>0.40</td>
<td>0.39</td>
<td>35</td>
</tr>
</tbody>
</table>

Figure 4.13 shows the best model performance in catchments 202111 and 107280 and the worst model performance in catchments 206041 and 102620. The poor performance of the model in 102620 can be attributed to the poor estimation of the recession constant, k. This catchment was identified as an outlier in the regionalisation with recessions for this catchment poorly described by the second order storage model. The models performed poorly in 206041 because the initial flow of the recession was estimated poorly. Analysis showed that the overall performance of models in predicting recession volumes was equally dependent on the success of the regional model for predicting AVE_k and AVE_Qo.

The differences between the observed and predicted 10-day flow values were further expressed as an equivalent depth over the catchment area. The absolute sign of this difference was taken so that over and under estimation within a single recession did not result in errors cancelling out (see Equation 19),

\[
\text{ABSERR}_{\text{DEPTH}} = \frac{3600 \times 24 \times 10 \times |Q_{\text{OBS}}^i - Q_{\text{PRED}}^i|}{(1000 \times A)}
\]

where \(Q_{\text{OBS}}^i\) and \(Q_{\text{PRED}}^i\) are for an individual 10-day flow period.

Hence the average error, expressed as an equivalent depth, could be calculated for each 10-day flow period between 1 October and 1 February, as shown in Figure 4.14. These average errors provide an estimate of the uncertainty associated with the prediction of the average annual recession for catchments in the HKH region. These results also confirm the good performance of the regional models. On average the error in estimating mid-January flows only represents a 4mm depth of water across the catchment.

Plotting the predicted recession against the observed hydrograph for an individual catchment can also give an indication of the performance of the regional models, as shown in Figure 4.15, for Nepalese catchment 106600, the Likhu Khola and Sangutar.

The results of these analyses suggest that the regional models provide a relatively good technique for estimating recession flows at ungauged sites. However, as with any regional models, there is inherent uncertainty due to the data used to construct the models. This is particularly so when a relatively small set of catchments are used, as was the case in this study. The data set is highly unlikely to be truly representative of the hydrological regimes in the HKH region and, therefore, in an operational context, opportunities to obtain and use measured local data (spot flow measurements, for example) should be actively pursued in order to reduce the uncertainty. The use of local data is discussed more fully below.
Figure 4.13 Illustration of the best and worst model performance

Figure 4.14 The variation of average ABSERR\_DEPTH (mm) for 10-day recession flows
4.14 Use of local data

Flow estimates from regional models, such as those described above, may be improved by incorporating local hydrological data. Two approaches are possible:

1. Making use of existing local data to refine the regional models for application in specific sub-regions, for example where additional gauging stations or data exist or are being developed.

2. Conducting spot-gauging programmes to monitor flows at key sites within catchments of interest and using this data to estimate recession parameters directly.

Both methods are illustrated using data from two catchments in the region: the West Rapti in Nepal and the Uhl (770 km² in area) in Himachal Pradesh.

4.14.1 Improved flow estimation using local analogue catchments – West Rapti

The long-term average recession for a catchment must consider a long period of flow record from which the behaviour during individual recessions is examined and an average recession curve/parameters identified. In ungaged catchments, an alternative method for obtaining a long-term average recession curve is offered by transposition of recession curve parameters from a similar (analogue) catchment. For example, the regional model for the recession constant, k, has catchment area as the only significant explanatory variable. However, it is acknowledged that other local factors including hydrogeology, steepness and snow and ice storage will also affect recession behaviour. Where some local data exists, for example, from analogue catchments with similar physiographic and hydrogeological conditions, there is an opportunity to improve the estimation of k.

The use of local data as a means of improving model estimates for recession flows was investigated in the West Rapti catchment of western Nepal. The catchment contains four gauging stations as shown in Figure 4.16. The observed recession parameters for each of the gauging stations are shown in Table 4.12.
Figure 4.16 Location of the four sub-catchments in the West Rapti basin, Nepal

Table 4.12 Station data for four sub-catchments in the West Rapti basin, Nepal

<table>
<thead>
<tr>
<th>STN</th>
<th>AREA</th>
<th>OBS_AVE_k</th>
<th>SD_k</th>
<th>N</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>103300</td>
<td>1980.0</td>
<td>202</td>
<td>62</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>103395</td>
<td>683.0</td>
<td>581</td>
<td>238</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>103500</td>
<td>3675.0</td>
<td>115</td>
<td>36</td>
<td>13</td>
<td>Significant artificial influences below 103500</td>
</tr>
<tr>
<td>103600</td>
<td>5086.0</td>
<td>155</td>
<td>44</td>
<td>23</td>
<td></td>
</tr>
</tbody>
</table>

On the basis of these observations the model for predicting AVE_k in the West Rapti was adjusted to:

\[
AVE_k = 316375 \times \text{AREA}^{-0.9664}
\]

Equation 20

The new “local” relationship between AREA and AVE_k closely follows the form of the regional model. The refined parameters in Equation 20 reflect the fact that the controls on recession behaviour within the West Rapti basin differ slightly from those occurring across the entire set of catchments used to develop the regional model. The new parameter values reflect the fact that recessions in the West Rapti are steeper (for a given catchment area) than the data for the regional models suggested.

As mentioned earlier, the lack of a relationship between the recession constant and some representation of hydrogeology is considered a weakness of the regional model. Application of the model in catchments having a very different hydrogeology to those represented in the data set should be undertaken with caution. For example, the lower portion of the West Rapti catchment contains some areas in the Terai region (a geological grouping of units on the Gangetic plain with soils derived from alluvium originating from Siwalik regions). None of the catchments in the data set contained significant proportions of these geological types.
A programme of spot-gaugings could be undertaken to investigate the recession behaviour in these areas, see subsequent Sections.

The observed Qo and To values for the four sub-catchments are shown in Table 4.13. Excluding station 103600, which is subject to significant artificial influences, the average AVE_Qo value of 47.8 mm and average AVE_To value of 269 days was calculated for the catchment.

<table>
<thead>
<tr>
<th>STN</th>
<th>AREA</th>
<th>MEAN ELEV</th>
<th>CV_ELEV</th>
<th>N</th>
<th>OBS_AVE_Qo (mm)</th>
<th>SD_Qo (mm)</th>
<th>DIST</th>
<th>OBS_AVE_To (days)</th>
<th>SD_To</th>
</tr>
</thead>
<tbody>
<tr>
<td>103300</td>
<td>1980</td>
<td>1644.7</td>
<td>0.311</td>
<td>15</td>
<td>44.0</td>
<td>13.8</td>
<td>7.6</td>
<td>271.73</td>
<td>14.6</td>
</tr>
<tr>
<td>103395</td>
<td>683</td>
<td>1804.2</td>
<td>0.301</td>
<td>16</td>
<td>54.5</td>
<td>23.0</td>
<td>8.0</td>
<td>272.63</td>
<td>16.4</td>
</tr>
<tr>
<td>103500</td>
<td>3675</td>
<td>1528.7</td>
<td>0.395</td>
<td>9</td>
<td>44.9</td>
<td>10.7</td>
<td>7.7</td>
<td>262.78</td>
<td>10.9</td>
</tr>
<tr>
<td>103600</td>
<td>5086</td>
<td>1245.1</td>
<td>0.575</td>
<td>12</td>
<td>36.9</td>
<td>14.5</td>
<td>8.2</td>
<td>271.67</td>
<td>16.4</td>
</tr>
</tbody>
</table>

The models for AVE_Qo and AVE_To were, thus, locally adjusted to:

\[
A V E _ Q o = \left[47.8 \times 1000 \times \frac{A R E A}{3600 \times 24 \times 10}\right]
\]

\[
A V E _ T o = 269
\]

As can be seen in Table 4.14 and Figure 4.17, the performance of the local data models greatly improves the estimation of the recession in each of the four sub-catchments. The relatively crude approximation of AVE_Qo (simple average of observed data) generally improves the estimation of initial recession conditions in all catchments.

<table>
<thead>
<tr>
<th>STN</th>
<th>BIAS_VOL</th>
<th>ERR_DEPTH (mm)</th>
<th>SRMSE (Oct 1 to Feb 1)</th>
<th>BIAS_VOL</th>
<th>ERR_DEPTH (mm)</th>
<th>SRMSE (Oct 1 to Feb 1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>103300</td>
<td>-0.34</td>
<td>-72.0</td>
<td>0.40</td>
<td>0.01</td>
<td>2.2</td>
<td>0.01</td>
</tr>
<tr>
<td>103395</td>
<td>-0.23</td>
<td>-57.0</td>
<td>0.24</td>
<td>0.15</td>
<td>36.8</td>
<td>0.21</td>
</tr>
<tr>
<td>103500</td>
<td>-0.48</td>
<td>-94.6</td>
<td>0.60</td>
<td>-0.05</td>
<td>-10.1</td>
<td>0.07</td>
</tr>
<tr>
<td>103600</td>
<td>-0.89</td>
<td>-144.6</td>
<td>1.05</td>
<td>-0.26</td>
<td>-42.2</td>
<td>0.27</td>
</tr>
</tbody>
</table>

4.14.2 Improved flow estimates using spot-gauging measurements

Spot-gauging measurements, using a current meter or dilution gauging equipment, are another means of reducing the uncertainty associated with flow estimates. The sampling error associated with observed average values of recession parameters Qo and k was used to estimate how many measurements would be required to give parameter estimates to a similar certainty level as the regional models. This enables a value to be assigned to the regional model estimates. The West Rapti catchment was used for illustrative purposes.

The average standard deviation of the observed Qo and k values for the three West Rapti gauging stations are shown in Table 4.15. Assuming that the true population of Qo values for each station are normally distributed (confirmed by inspection), then the Central Limit Theorem can be used to estimate the number of measurements of Qo, or k, needed to obtain an estimate
of AVE_Qo, or AVE_k, to certain levels of accuracy, at given levels of confidence. The adopted critical level of accuracy was ± 45%, which was comparable to the f.s.e. for the regional equations for AVE_Qo and AVE_k.

Figure 4.17 Regional models vs local data models in four West Rapti sub-catchments

These results suggest that a programme of approximately four spot-gauging measurements a year for a four to six year period should provide parameter estimates to levels of accuracy comparable with regional models.

Table 4.15 Number of measurements of flow needed to estimate AVE_Qo and AVE_k to an accuracy of ±45%, at a 95% level of confidence

<table>
<thead>
<tr>
<th>STN</th>
<th>AVE_Qo (cumecs)</th>
<th>SD_Qo (cumecs)</th>
<th>AVE_Qo nCRIT for 95% confidence</th>
<th>OBS_AVE_k (x10^8)</th>
<th>SD_k</th>
<th>AVE_k nCRIT for 95% confidence</th>
</tr>
</thead>
<tbody>
<tr>
<td>103395</td>
<td>43.1</td>
<td>18.2</td>
<td>6</td>
<td>581</td>
<td>238</td>
<td>6</td>
</tr>
<tr>
<td>103300</td>
<td>100.9</td>
<td>31.6</td>
<td>5</td>
<td>202</td>
<td>62</td>
<td>5</td>
</tr>
<tr>
<td>103500</td>
<td>190.8</td>
<td>45.3</td>
<td>4</td>
<td>115</td>
<td>36</td>
<td>5</td>
</tr>
<tr>
<td>103600</td>
<td>218.7</td>
<td>85.4</td>
<td>-</td>
<td>155</td>
<td>44</td>
<td>-</td>
</tr>
</tbody>
</table>

This analysis also places a value on the regional model estimation in terms of potential savings in time and resources. For example, an estimate of AVE_k from the regional model is worth approximately 20 flow gaugings made over a five-year period, whereas an estimate of AVE_Qo from the regional model is worth approximately four to six flow gaugings made in individual years. It should be noted that these results assume zero hydrometric error in the spot-gauging and only address the issue of sampling error associated with the long-term average value of
recession parameters $Q_o$ and $k$. The use of spot-gaugings is very important in the data-sparse HKH region and the following two sections report on spot-gauging programmes undertaken in the West Rapti catchment (Nepal) and Uhl catchment (Himachal Pradesh).

### 4.14.3 Preliminary fieldwork results – West Rapti

An example is presented of how spot-gauging information may be used to estimate the recession curve for the catchment upstream of Bagasoti gauging station (103500) on the Rapti. This station was not used to develop any of the regional models for recession curve parameters. Figure 4.18 shows the observed long-term average hydrograph (with 95 percentile confidence limits on sampling error) together with spot-gauging data, derived from fieldwork by DHM from December 2001 to June 2002 and historical data compiled by Tahal Engineering Consultants (Tahal, 2002).

![Figure 4.18 Observed long-term average annual hydrograph and spot-gaugings at Bagasoti GS](image)

Any spot-gauging programme should be designed to capture the initial portion of the recession, since $Q_o$ and $T_o$ are defined by the date of the first measurement. The recession start date was found to be relatively invariant between Rapti sub-catchments (around 26th September). The recession constant, $k$, was estimated using linearisation techniques which fit a second order recession curve model to the data points. The resulting recession curve parameters are shown in Table 4.16 and the predicted recession curves are shown in Figure 4.19.

### Table 4.16 Comparison of recession curve parameters estimates for catchment 103500

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$k$ ($10^{-8}$)</td>
<td>115</td>
<td>86</td>
<td>62</td>
<td>69</td>
<td>56</td>
</tr>
<tr>
<td>$Q_o$ (m$^3$/s)</td>
<td>190.8</td>
<td>314.8</td>
<td>47.840</td>
<td>735.290</td>
<td>26.644</td>
</tr>
<tr>
<td>$T_o$</td>
<td>18/Sep</td>
<td>23/Sep</td>
<td>17/Nov</td>
<td>25/Aug</td>
<td>10/Jan</td>
</tr>
</tbody>
</table>

*Note: [1] $n$ is the number of spot-gaugings made that were used in the linearisation process to determine $k$. |
It should be noted that the observed data is for long-term average recessions not recessions associated with individual years. All spot-gauging data sets indicated a flatter recession than the observed average annual recession. This may be because the construction of the average annual recession used only those portions of the observed hydrograph which were associated with a recession, i.e. post monsoon flows that were progressively decreasing. Some of the spot-gauging data collected towards the end of the recession period (late March) could be influenced by local rainfall events, which signal the end of the recession and the beginning of the monsoon. Furthermore, it is possible that the actual recession during 2000 and 2001 is flatter than average, and hence the k values obtained by analysis of these recessions were lower than the long-term recession constant.

The results show the importance of capturing the initial recession flows within the spot-gauging programme. The DHM data measured in January 2001 and the Tahal spot-gaugings of 2000 failed to capture the initial storage state of the catchment. Although the recessions estimated from these data are somewhat flatter than those from observed data, they do reflect the subsequent recession behaviour, see Figure 4.19. The Tahal data for 2001 captures a very high initial flow (probably still during the monsoon period), which effectively overestimates the catchment storage and hence overestimates the flows during the following recession period.

Figure 4.19 illustrates that the average initial recession flow (AVE_Qo) is responsible for the systematic over-estimation of flows during the recession period. The recession constant AVE_k predicted by the regional models was quite good.

![Figure 4.19 Predicted and observed recession curves for catchment 103500](image)

The two spot-gauging programmes therefore provided reasonable estimates of the long-term recession behaviour and could be used to improve identification of the initial recession flow in the regional model. Further improvements could be made by carrying out spot-gaugings in subsequent seasons at the same sites, with flows measured mid monthly beginning in September and ending in December (four readings).
4.14.4 Preliminary fieldwork programme results – Uhl

The Alternate Hydro Energy Centre (AHEC), Roorkee carried out a spot-gauging programme in the Uhl catchment over the period November 2001 to March 200. Flow measurements were made at four sites with additional flow data available at a fifth site (FMS 5). The Barot gauging station (see Figure 4.20) is located just upstream of an off-take for a 40MW hydropower station. Water is removed from the Uhl catchment at this point and is discharged into a neighbouring catchment to the west. Records indicate that the hydraulic capacity of the off-take is approximately 20 m³/s, which generally exceeds all natural flows at this point from October to February and, during this period, all water is diverted to the neighbouring catchment.

![The Uhl catchment, showing the location of flow monitoring sites](image)

The spot-gauging programme was unable to adequately capture the initial recession periods at any of the four flow monitoring sites. Flow data for Barot suggested that monitoring should have begun in August rather than November, but access difficulties and flow conditions prevented this from being achieved. However, the data collected represent a good starting point.

The recession parameter estimates for FMS 5 are shown in Table 4.17, and the predicted recession curve in Figure 4.21. This also shows an observed hydrograph for the Barot catchment and the recession predicted using the parameters determined by the regional models.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Observed data at the Barot gauging station</th>
<th>Regional model at FMS 5</th>
<th>Spot-gaugings at FMS 5 (AHEC) (n=5^{[1]})</th>
<th>Spot-gaugings at FMS 5 (AHEC + PSEB)(^{[2]}) (n=5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(k \times 10^{-8})</td>
<td>709</td>
<td>1864</td>
<td>369</td>
<td>1509</td>
</tr>
<tr>
<td>(Q_0 \text{ (m}^3\text{/s)})</td>
<td>23.6</td>
<td>9.7</td>
<td>2.15</td>
<td>6.6</td>
</tr>
<tr>
<td>(T_o)</td>
<td>16/Sept</td>
<td>27/Aug</td>
<td>1/Oct</td>
<td>21/Aug</td>
</tr>
</tbody>
</table>

Notes:

[1] \(n\) is the number of spot-gaugings made during the recession that were used in the linearisation process used to determine \(k\).

[2] makes use of four AHEC spot flows at FMS 5 and a single reading at Barot on 21 August 2001, re-scaled for the catchment area above FMS 5.
The recessions estimated from spot-gaugings tend to be flatter than those predicted by the regional model. This may be because the 2001/2002 recession began earlier than the long-term average recession and, hence, a flatter portion of the curve occurs between September and January. However, the fit of both models is relatively good over the low flow period October to February.

![Figure 4.21 Estimation of recession at FMS 5 in the Uhl catchment](image)

### 4.15 Conclusions

The application of a second order recession curve model to flow data from catchments in the HKH region was found to be appropriate to enable long-term average recessions to be predicted. The general Horton-Izzard model (Dooge, 1973) was used and zero inflows during the recession periods were assumed. The validity of this assumption was confirmed by inspection of available data sources. A long-term average recession was identified for each of the catchments in the quality controlled data set, defined by use of the average values of the recession parameters $k$ (recession constant), $Q_0$ (initial recession flow) and $T_0$ (the start date of the recession period) obtained from individual recessions. The regional models developed using catchment characteristics to predict recession curve parameters were able to simulate the long-term recession behaviour of catchments in the data-set. The relationships suggest:

- The recession constant ($k$) is primarily dependent on catchment area, with smaller catchments showing steeper recessions. The data available did not allow relationships between the recession constant and hydrogeology to be identified. However, conceptually, such relationships should exist and a field campaign designed to capture recession behaviour in small catchments with a very different permeability would begin to address this knowledge gap. The application of the model in catchments with a very different
hydrogeology to those represented in the data set should be undertaken with caution. Furthermore, larger data sets would need to be examined to assess whether the second order model was the most appropriate for all catchments in the region. The poor performance in catchment 102620 may have been due to an inappropriate choice of storage model or could be related to hydrometric errors in the data.

- The initial recession flow (Qo) is highly correlated with annual catchment runoff, with “wetter” catchments having higher Qo values. The regional models for estimating Qo were not able to include a measure of catchment rainfall, which would be highly correlated with catchment runoff, due to high levels of uncertainty in rainfall data sets. Within Nepal, where better rainfall data was available, the importance of annual rainfall for determining Qo was evident. Improvements to the regional model for estimating initial recession flow are likely to be realised if a better, consistent characterisation of rainfall for the HKH is developed.

- The variability of the start date for recessions (To) was effectively described by a model including geographic location and average catchment elevation. The relationships suggest that recessions begin earlier in the west of the HKH, where the proceeding monsoon season is less severe, and earlier at higher elevations, perhaps reflecting the fact that moisture is being trapped as snow/ice earlier at higher altitudes. The within-year variability of To was found to be relatively low for a given catchment and it may be possible to source this type of information from local hydrologist. Building up a picture of the timing of the beginning of the dry-season across the region from local knowledge could be used to improve the regional model for To. To estimated from the regional model is also suitable for use in planning the timing of field campaigns to capture Qo and to quantify recession behaviour.

The regional models for k, Qo and To were evaluated over an independent data set of 14 Nepalese catchments. The performance of the models did not deteriorate significantly, suggesting they were relatively robust. However, it is acknowledged that the data set (including the evaluation catchments) was still relatively small and cannot be regarded as completely representative of all conditions experienced in the HKH region. Planned extensions to the hydrometeorological networks in the region will yield additional data sets that will eventually enable the hydrological characteristics of the region to be sampled better.

Given the limited data the performance of the regional models for estimating long-term annual recessions was very good. Of the 39 catchments, the BIAS_VOL (the percentage error in the estimation of the volume of flow occurring between 1 October and the 1 February) was within ±25% for 22 catchments (i.e. 64% of the data set), and 32 of the 39 catchments had BIAS_VOL values within ±50%. The prediction of the mid-January flow (11 Jan) was within ±50% for 32 of the 39 catchments, and the average absolute error expressed as an equivalent depth (ABSERR_DEPTH) was less than 5 mm for 27 of the catchments.

The use of local spot-gauging programmes to improve the estimation of recession behaviour was explored. Based purely on sampling error the uncertainty associated with the recessions estimated using the regional models was approximately equivalent to the sampling error associated with a six-year programme of five spot-gaugings each year. Hence, the relative value of the regional models may be assessed. Examination of spot-gauging data in two pilot catchments, the West Rapti (Nepal) and the Uhl (Himachal Pradesh), illustrated the importance of planning fieldwork to coincide with the initial recession flows. Comparisons between the long-term recession parameters predicted by the regional models and those estimated from spot-gauging data showed general agreement. Spot-gauging programmes were identified to be very useful for improving the estimation of Qo. A well planned spot-gauging programme, designed to collect data in a systematic manner over several years, represents one of the best methods for improving the understanding of local hydrology in a data-sparse region like the HKH.
The development of models for estimating the average annual recession provides water resource managers with the ability to not only estimate the magnitude of flows in ungauged catchments, but also the timing of these flows. This represents significant advantages over techniques such as flow duration curve statistics, such as WECS (1990) and Singh et al. (2001), which lose the temporal sequencing of flows. Hence, recession curve prediction is particularly well suited for application in the management of irrigation-type schemes, where water use can be matched to crop growth requirements at the various stages of the agricultural calendar.
5 Implementation of an IWRM tool


5.1 Introduction

Water resource management fundamentally requires estimates of water availability. Typically, such estimates will quantify the amount of water available at specific times of the year or will provide indications of the frequency at which specified flows will occur. Where gauging stations have been well established, analysis of historic flow records will provide the necessary information. However, in many instances estimates are required in catchments where there is very little or no data available. Few catchments remain unaffected by human activity. In catchments where there are significant uses of surface water and groundwater resource, effective water resources management is enabled by differentiating the “natural” component of river flow from the “influenced” component. In many parts of the world Integrated Water Resources Management (IWRM) tools have been developed to help water resources managers and planners to estimate both natural and influenced water availability and to equitably apportion the resource between users. In this project, a prototype IWRM tool was developed for two specific basins, the West Rapti in Nepal and the Uhl in Himachal Pradesh, to demonstrate the potential for improved water resources management in the HKH. The prototype would show managers how such a tool could help to assess the impacts of existing and future water management schemes on water availability. It could, for example, provide a strategy for managing the abstractions of a proposed irrigation scheme without compromising the needs of downstream users.

An IWRM tool was designed to address two key issues of water resource management. Firstly, the tool enables estimates of the natural low flows in ungauged catchments to be derived using a robust hydrological model (i.e. the regional recession curve model described in Chapter 4). Secondly, it enables the impact of water use or “artificial influences” within the catchment to be simulated. The system includes a number of components:

- A Geographical Information System (GIS) based interface, enables digital data sets to be displayed, including a river network from which catchments can be automatically defined. The GIS based approach is well suited to catchment studies, enabling the visualisation of the catchment in physical terms and providing the ability to overlay contextual information to aid resource assessments.

- An underlying database, to hold geographically referenced information relating to water use within the catchment. Mapping software tools can be used to access the relevant information from the underlying database, based on geographically defined searches. For example, all abstraction points within a catchment can be selected and the information stored against these features displayed and manipulated.

- Hydrological models, linked to GIS and database information on water use, enable both natural and influenced flow conditions to be simulated. The hydrological models, estimating natural low flow conditions, require the definition of the ungauged catchment area from a specified point on a digital river network, the collection of relevant catchment characteristics from spatial data sets, followed by the application of the regional low flow estimation algorithms. The water use information on relevant artificial influences within the ungauged catchment are then accessed and models applied to estimate the impact of these net influences on the predicted natural hydrology.
Interactive reporting forms, supplying the user with the results of the hydrological analysis, enabling manipulation of artificial influences and scenario analysis.

The prototype IWRM tool was developed as a PC-based software package, written in MS Visual Basic, using MS Access as the database and ESRI MapObjects for mapping and geographical analysis. The prototype software was a derivative of the Low Flows 2000 IWRM software that CEH had developed for the Environment Agency in England and Wales, albeit tailored specifically for the two HKH catchments and incorporating the new regional hydrological model described in Chapter 4.

The remainder of this chapter describes the implementation of the new model within the prototype IWRM software tool and details how the tool was applied and tested in both the West Rapti and Uhl catchments. These areas were chosen in consultation with local stakeholders as areas where water resource management issues were developing. The chapter describes how the software was ultimately demonstrated to stakeholders at workshops in India and Nepal and presents their views on the usefulness of such a product and prospects for its implementation elsewhere in the region.

5.2 Implementation of the regional hydrological model

The development of a new regional hydrological model for estimating the natural recession flows of ungauged catchments in the HKH was described in detail in Chapter 4. To implement the model, a 1km x 1km elevation grid was incorporated within the software. For both the Wet Rapti and the Uhl, a digital river network of the basin was also defined and digitised from 1:50 000 topographic map sheets and brought into the software. The software uses the digitised river network to define the upstream catchment boundary upstream of any selected point on a river. This boundary is then used to extract catchment average values from the digital elevation grid in order to derive the catchment characteristics that are necessary to define the three parameters (k, Qo and To) of the hydrological model. The catchment boundary is also used to identify artificial influences (abstractions, discharges, impounding reservoirs) occurring within the catchment from geo-referenced digital data sets of these influences.

The catchment boundary definition routine is an automated procedure that is initiated by the user’s selection of a catchment outlet. The catchment boundary is defined according to the vectored digital river networks and an approach, described by Sekulin et al. (1992), in which grid cells are assigned to each river reach based on a shortest distance algorithm and constrained, or guided, by existing digitised catchment boundaries (see Figure 5.1). As with the river network, main sub-catchment boundaries were digitised from 1:50,000 scale topographic maps for both catchments. The accuracy of the catchment definition is constrained by the density of guiding boundaries, the density (and spatial variation in density) of the river network and the resolution of the grid used within the method. Within the IWRM tool, a grid of 200m x 200m was used as the best compromise between speed of application and accuracy of estimation within small catchments.

Once a catchment has been defined, the software displays the catchment characteristics and the corresponding recession parameters. The resulting estimated natural recession curve is also displayed (Figure 5.2). At this point the user may modify the three recession curve parameters (k, Qo and To) and re-plot the natural curve. Where local data is available, this enables improved estimates of any of the recession curve parameters to be readily applied. For example, re-scaling of an observed Qo from an analogue catchment could be used to provide a new estimate of Qo for the ungauged site. Alternatively, local information on the timing of the recession may be available to provide an improved estimate of To. The software allows the mean monthly flows associated with the estimated recession curve to be accessed in tabular
format, which in turn may also be exported to standard spreadsheet and word processing packages.

![Figure 5.1 Automated catchment climb by cell-association method](image1.png)

**Figure 5.1 Automated catchment climb by cell-association method**

![Figure 5.2 Display of the estimated natural recession curve and mean monthly flows](image2.png)

**Figure 5.2 Display of the estimated natural recession curve and mean monthly flows**

### 5.3 Representation of water-use within a catchment

Point sources of water use are defined in a geographically referenced manner within the software as a digital layer in a “Shape File”. All “artificial influences” within a catchment boundary may then be identified using MapObjects “Point to Polygon” routines. Once the relevant influences have been identified and their details registered on the underlying database,
the database may be interrogated to retrieve information quantifying the hydrological impact of each influence and, hence, the cumulative impact may be determined.

### 5.3.1 Artificial Influences

The types of water-use that can be simulated within the IWRM tool are summarised in Table 5.1. Four primary types of artificial influence are accommodated in the software: surface water abstractions, where water is abstracted (pumped) or diverted from a river; groundwater abstractions, where water may be pumped from a borehole or well; discharges, where used (effluent) or unused water is returned to surface water; and reservoirs or impoundments, where water is stored and released downstream in a regulated manner. The water-use associated with each type of influence is quantified by 12 average monthly volumes of water abstracted or discharged to the river, termed a “monthly profile”. The basis for the monthly profile and examples of each type of water use are also shown in the table. Information relating to each of these influence types, or “feature” types, is stored in the underlying database in a hierarchical manner, as shown in Figure 5.3.

#### Table 5.1 Summary of the types of water use that can be represented in the IWRM tool

<table>
<thead>
<tr>
<th>Feature</th>
<th>Monthly profile</th>
<th>Typical examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface water abstraction</td>
<td>Volumes of water abstracted directly from surface water sources.</td>
<td>Water obtained for irrigation using diversion canals</td>
</tr>
<tr>
<td>Groundwater abstraction</td>
<td>Volumes of water abstracted from a groundwater source remote from the river.</td>
<td>Water pumped from boreholes for irrigation</td>
</tr>
<tr>
<td>Discharge</td>
<td>Volumes of water returned to, or discharged, to the river</td>
<td>Water returned to the river from hydropower schemes</td>
</tr>
<tr>
<td>Reservoir or impoundment</td>
<td>Net volumes of water passing the reservoir, combination of spills and releases made</td>
<td>Reservoirs established for hydropower generation</td>
</tr>
</tbody>
</table>

#### Figure 5.3 Hierarchical data structure for abstractions, discharges and impoundment

The top-level feature is a Licence that may own a number of Sites, which, in turn, may have multiple Purposes. Information stored at the Licence-level includes a licence owner, the owner’s address etc. Site-level information is related to a particular point by a grid reference. Most importantly, the net monthly profile is stored at the Site-level, as it must be related to the geographic location at which the artificial influence acts. Purpose-level data relates to how the water is used at a particular site. For example, water from one abstraction point may be used for both domestic consumption and irrigation.
5.3.2 Monthly profiles
The water use of a particular artificial influence is quantified by its monthly profile. Monthly profiles are stored at the Purpose-level and, hence, represent the seasonal pattern of water use for a specific purpose, for example irrigation of a particular crop type. For multi-purpose sites, these Purpose-level profiles are then summed to give a Site-level profile which is associated with a geographic location, representing the point at which water is abstracted/discharged/released from an impoundment. Alternatively, a Site-level monthly profile may be entered directly for a single-purpose feature or for a multi-purpose feature where there is no desire to hold finer resolution information on seasonal water use.

The monthly profile data for a particular feature are defined by the user using the data interface of the IWRM software. A profile should represent the average water use in each calendar month, since the objective is to simulate the long-term conditions for the catchment, with respect to both the natural hydrology and influences. Possible sources of data that can be used to determine long-term average monthly profiles would include:

- Recorded flows through irrigation schemes – these could be based on canal or pump capacity, irrigated area and crop water usage;
- Recorded or estimated return flows (discharges) from irrigation area;
- Records from water transfer schemes;
- Intermittent measured flow rates in diversion canals across a cropping season;
- Pump run-time information from pumping stations abstracting water from boreholes or surface water supplies;
- Records kept at hydropower sites of total diverted flows, spills and releases;
- Discharge records from industrial/domestic water and wastewater treatment plants.

Without recorded information, estimates of the net water use at a particular feature must be made. For discharges, these may be determined by design criteria associated with treatment plants, associated abstractions or other methods. It is very difficult to estimate release regimes from impoundments and it is suggested, therefore, that detailed investigations be undertaken to establish realistic monthly profiles for such features.

5.3.3 Crop water requirement tool
Given that approximately 90% of the water abstracted in Asia is associated with irrigated agriculture (FAO, 1999), a tool was developed specifically for the prototype IWRM software to enable prospective users to estimate the water requirements, in the form of a Purpose-level monthly profile, based on the crop water requirement (CWR) of the irrigated land.

In the absence of abstraction records, a method was developed to estimate the rate of abstraction associated with irrigation of particular crop types over a specified area of land, based on the water requirements of the crop. The Crop Water Requirement (CWR) is defined by the Food and Agriculture Organisation as “the depth of water needed to meet the water loss through evapotranspiration of a disease-free crop, growing in large fields under non restricting soil conditions including soil water and fertility and achieving full production potential”. Following the FAO approach (FAO, 1991), the CWR is expressed as a depth (mm) of water which can be converted to an abstraction volume if the area of irrigated land is known. The FAO methods and parameter values for estimating CWR were adopted to provide an initial estimate of water use, which could then be modified by local practitioners. The basic formula for calculating the evaporative demand exerted by a crop is shown in Equation 1 below;

\[ \text{ET}_{\text{crop}} = \text{ET}_{\text{O}} \times K_c \]

*Equation 1*
Where \( E_{To} \) is the evapotranspiration demand of a reference crop (grass) in given climatic conditions and \( Kc \) is the crop coefficient.

This equation incorporates both the effect of transpiration and soil evaporation into a single \( Kc \) value which is allowed to vary throughout the growing season. The CWR tool, as implemented within the IWRM software, requires the user to define a number of parameters for a particular abstraction, while providing defaults (that may be modified by the user) for other parameters, see Table 5.2.

**Table 5.2 Data requirements for the CWR estimation method**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Symbol</th>
<th>Definition</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crop type</td>
<td>( \text{TYPE} )</td>
<td>Defines appropriate default crop water requirement parameters</td>
<td>User defined</td>
</tr>
<tr>
<td>Irrigated area</td>
<td>( \text{AREA} )</td>
<td>Scales crop water requirement from a unit depth to volumetric quantity</td>
<td>User defined</td>
</tr>
<tr>
<td>Irrigation start date</td>
<td>( \text{START} )</td>
<td>Defines length and timing of irrigation period</td>
<td>User defined</td>
</tr>
<tr>
<td>Irrigation end date</td>
<td>( \text{END} )</td>
<td>Defines length and timing of irrigation period</td>
<td>User defined</td>
</tr>
<tr>
<td>Length of irrigation period</td>
<td>( \text{LEN} )</td>
<td>Length of irrigation period (END-START) in days</td>
<td>Calculated</td>
</tr>
<tr>
<td>Net irrigation efficiency</td>
<td>( E_{IRR} )</td>
<td>Defines net efficiency of irrigation system</td>
<td>User defined / Default</td>
</tr>
<tr>
<td>Length of initial season</td>
<td>( \text{L}_{\text{INI}} )</td>
<td>Fraction of LEN for initial season</td>
<td>Defaults from [1]</td>
</tr>
<tr>
<td>Length of development season</td>
<td>( \text{L}_{\text{DEV}} )</td>
<td>Fraction of LEN for development season</td>
<td>Defaults from [1]</td>
</tr>
<tr>
<td>Length of mid season</td>
<td>( \text{L}_{\text{MID}} )</td>
<td>Fraction of LEN for mid season</td>
<td>Defaults from [1]</td>
</tr>
<tr>
<td>Length of late season</td>
<td>( \text{L}_{\text{LATE}} )</td>
<td>Fraction of LEN for late season</td>
<td>Defaults from [1]</td>
</tr>
<tr>
<td>Initial crop coefficient</td>
<td>( \text{Kc}_{\text{INI}} )</td>
<td>Crop coefficient applicable to initial season</td>
<td>Defaults from [2]</td>
</tr>
<tr>
<td>Mid-season crop coefficient</td>
<td>( \text{Kc}_{\text{MID}} )</td>
<td>Crop coefficient applicable to mid-season</td>
<td>Defaults from [2]</td>
</tr>
<tr>
<td>End-season crop coefficient</td>
<td>( \text{Kc}_{\text{END}} )</td>
<td>Crop coefficient applicable to end-season</td>
<td>Defaults from [2]</td>
</tr>
<tr>
<td>Monthly reference evapotranspiration demand</td>
<td>( E_{ToI} )</td>
<td>Predicted evapotranspiration demand of the reference crop (grass)</td>
<td>User defined</td>
</tr>
<tr>
<td>Monthly effective rainfall</td>
<td>( \text{EFFRF}_{I} )</td>
<td>Effective rainfall in month ( I )</td>
<td>User defined</td>
</tr>
</tbody>
</table>

Notes:

The data entered enables a crop coefficient curve to be developed for a specific crop type. This curve represents an estimate of \( ETC_{\text{rop}} \) on a daily basis throughout the crop cycle. The water use by plants changes throughout the growing season, as shown in Figure 5.4, in response to changes in vegetation and ground cover occurring at the various stages of plant growth. The standard FAO procedure (Allen et al., 1998) has been used to define \( Kc \) at three stages of growth; the initial stage (\( Kc_{\text{INI}} \)), development stage (\( Kc_{\text{MID}} \)) and the late season stage (\( Kc_{\text{END}} \)). These data, combined with information regarding the growing season lengths can then be used to construct a crop coefficient curve for a particular location.

Local data relating to crop coefficient curves should be used where it exists. However, the default values for the crop coefficients and lengths of growing season that are incorporated within the software have been derived from Allen et al. (1998) for a number of crop types.
pertinent to the HKH region. A summary of the main irrigated crop types in the HKH region is contained in Table 5.3.

**Table 5.3 Dominant crop types in the HKH region (Source: Tripathi and Sah, 2001)**

<table>
<thead>
<tr>
<th>High Mountain  (&gt;1700m)</th>
<th>Middle Mountain (1000m to 1700m)</th>
<th>Valleys (Siwalik and Terai) (&lt;1000m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cereals</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maize</td>
<td>Rice</td>
<td>Rice</td>
</tr>
<tr>
<td>Barley</td>
<td>Maize</td>
<td>Maize</td>
</tr>
<tr>
<td>Buckwheat</td>
<td>Wheat</td>
<td>Wheat</td>
</tr>
<tr>
<td>Wheat</td>
<td>Barley</td>
<td>Barley</td>
</tr>
<tr>
<td>Vegetable</td>
<td></td>
<td></td>
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<tr>
<td>French bean[1]</td>
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<tr>
<td>Cabbage[1]</td>
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<tr>
<td>Tubers</td>
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<tr>
<td>Potato</td>
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<tr>
<td>Potato</td>
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<tr>
<td>Pulses</td>
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<tr>
<td>Oil crops</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mustard</td>
<td>Rapeseed (Canola)[1]</td>
<td></td>
</tr>
<tr>
<td>Fruit</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Apples[1]</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

![Figure 5.4 Schematic diagram of a crop coefficient curve](image)

Tables 11 and 12, from Allen et al. (1998), were used to derive estimates of Kc and growing season length parameters respectively. The lengths of growing season were converted to fractions of the net growing season so that user-defined start and end dates could be applied. It should be noted that the coefficients (Kc) and growing season parameters adopted are only approximations and local experts (agronomists, irrigation engineers) should be consulted to obtain site specific parameter values. Furthermore, all Kc values, with the exception of those for rice, have not been modified for the impact of humidity and wind speed. Allen et al. (1998)
should be consulted for further guidance. Furthermore, no adjustments have been made for local conditions such as the size of fields, soil conditions, water stress, salinity levels and irrigation practices. These would need to be included in the estimation method by adjustment of the predicted crop coefficients.

The data entry form associated with the CWR tool is shown in Figure 5.5. The user is initially presented with the default values of variables associated with the chosen crop type, but is then able to modify all of the variables as required. Once a final crop coefficient curve has been identified by the user on the CWR data entry form, then the calculation of the monthly profile associated with the abstraction for this irrigation regime is made using the irrigated area of land (AREA), the irrigation efficiency (EIRR) and monthly average effective rainfall (EFFRF) estimates. This initially calculates daily water use (m³) which is then averaged over a month to produce the final monthly profile. The final monthly profile associated with a purpose is then automatically transferred from the CWR tool to the Purpose-level monthly profile in the software, see Figure 5.6. Where more than one purpose exists, the Purpose-level profiles are summed to generate the Site-level monthly profile which the user can edit.

5.3.4 Calculation of influenced flows

The first step in calculating influenced flows for the ungauged catchment is to determine the cumulative impact of all upstream artificial influences. The net impact of these artificial influences in each month can be represented by a monthly influence profile that allows the seasonal variations in certain operating regimes to be taken into account. This process requires firstly the identification of influences within the catchment, discounting of areas above impounding reservoirs and finally summation to produce a net monthly profile.
The identification of all occurrences of artificial influences within the user-defined catchment is accomplished using the automatically generated catchment boundary. This boundary is overlaid onto the ShapeFile containing the points representing the geographic location of the artificial influences, using the MapObjects “Points from Polygon” routine to select all those points within the catchment boundary.

The impacts of an impounding reservoir are incorporated using the following steps.

- For any impoundments that lie within the ungauged catchment, the software identifies those that lie immediately upstream of the ungauged site and estimates the catchment boundaries for the impounded catchment(s).
- All influences within the impounded catchment(s) are then identified and discounted from the list of influences above the ungauged site of interest.
- The natural flow statistics are estimated for the incremental catchment, which is the catchment that lies between the location(s) of the impounding structure(s) and the ungauged site of interest (Figure 5.7).

The influence profile(s) for the impounding reservoir(s) are then treated as discharges to the ungauged, incremental catchment.

Abstractions from groundwater do not have an immediate impact on the flows in the rivers as a result of the complex response of stream flow to the pumping of water from an unconfined, or semi-confined aquifer. In reality, for an individual well, the impact of the abstraction on the river flow is dependent upon such factors as: the bulk aquifer hydrogeology and geometry; distance of borehole from stream; the seasonality of pumping; the pumping rate; the degree of hydraulic connection between the stream and aquifer; and local features such as swallow holes and spring lines. Two Site-level monthly profiles exist for groundwater abstractions.
normal monthly profile contains 12 values representing the volumes of water abstracted at the borehole. The Stream Depletion Volumes (SDV) are 12 values that represent the impact of the monthly profile on the nearest river reach and are used to calculate a net monthly profile for a catchment.

Finally, all monthly profiles for surface water abstractions, SDVs for groundwater abstractions, monthly profiles for discharge and reservoir impacts for each identified artificial influence are summed to produce a net monthly abstraction. Discharges and impoundment releases are considered positive and abstractions as negative values. The calculated net monthly influence profile can be:

- negative in all months in a catchment in which abstractions exceed discharges throughout the year;
- positive in all months in a catchment in which discharges exceed abstractions throughout the year;
- or positive and negative in different months in more complex catchments, particularly when seasonal abstractions are significant.

The net monthly profile and resulting influenced recession curve may be displayed individually or together.

**Figure 5.7** Schematic representation of the treatment of impounding reservoirs

### 5.4 Implementation of the prototype IWRM in the Uhl catchment

The Uhl catchment is located in the Kangra and Mandi Districts of the northern state of Himachal Pradesh, India. The headwaters of the catchment contain some areas of permanent snow and reach a maximum elevation of 5000 m. The major tributary, the Lambadag flows from the north east and joins the Uhl above the town of Barot. The Uhl then flows about 60 km in a north-to-south direction to join the Beas River at an elevation of about 800 m. The catchment is characterised by steeply incised valleys with heavily forested north-facing slopes. The population is restricted to living in small hill villages and larger towns in the main valley floor, alongside which irrigated agriculture is found.
Water is diverted via a tunnel from the Uhl downstream of Barot to the 40MW Shanan hydro-power station, located at Jogindernagar in a catchment west of the Uhl (Figure 5.8). None of the water supplied to the power station is returned to the Uhl catchment. Hence, during the dry-season, flows downstream of Barot approach zero. Figure 5.9 shows the hydrograph of the river recorded at the Barot gauging station and the estimated flows supplied to the Shanan power station.

*Figure 5.8 Location of the Uhl catchment in Himachal Pradesh*

The Uhl catchment provides a good illustration of where water assessments are important. The diversion for the hydropower station is currently designed to remove all dry-season flows. Clearly this has a significant effect on the availability of water for irrigation purposes at all points downstream. The linear nature of the Uhl means that progressive management of water in a downstream direction is necessary to ensure availability for all water users (Figure 5.10). This figure also shows the location of flow monitoring site number 2 (FMS 2) representing a point in the catchment where spot gaugings were undertaken to capture flows during recession periods (see Chapter 4).
Figure 5.9 Flows recorded at Barot and flows diverted to the Shanan hydropower station

Figure 5.10 Map of the Uhl catchment
The prototype IWRM tool was used to model the hydrology of the Uhl catchment and to enable different water use scenarios to be investigated. For simplicity, only the diversion of water from the Uhl at Barot (for the Shanan hydropower station) was modelled. This is, by far, the largest influence in the catchment and will have the most significant impact on all water use downstream. The Site-level information (including the monthly profile) entered for the Barot off-take is shown in Figure 5.11.

The IWRM tool was used to estimate the natural flows at the Barot gauging station, which were compared with the observed average monthly flows (PSEB data), as shown in Figure 5.12. As can be seen, the predicted recession curve agrees well with the observed data at this point.

The impact of the Shanan hydropower station abstraction at the most downstream flow monitoring site (FMS2) in the Uhl was simulated using the IWRM tool. Figure 5.13 shows the influenced and natural flow estimates for the catchment, together with the characterisation of the abstraction at Barot, for the Shanan hydropower station.

A scenario tool facility within the software enables changes to abstraction regimes to be simulated and the resulting impact on flows reviewed in relation to the natural flows and the influenced flow under current management conditions. Figure 5.14, for example, illustrates the impact on flow at FMS2 of increasing and reducing the amount of water abstracted at Barot for the Shanan hydropower station. This type of scenario analysis enables the user to readily investigate the effects that changes in water policies, regulatory controls, pricing factors, cropping patterns and crop selection will have on regional water availability.

Figure 5.11 SITE level information the abstraction for the Shanan hydropower plan.
Figure 5.12 Comparison of the estimated and observed flows at Barot

Figure 5.13 Estimation of influenced flows at FMS2
5.5 Implementation of the prototype IWRM in the West Rapti basin

The West Rapti River rises in the Middle Mountain region of west Nepal (Figure 5.15). It is a perennial river, with no snowmelt contribution to flow, but has alluvial aquifer systems within the basin. The area of the basin at the downstream gauging station at Jalkundi (103600) is 5150 km². Elevation ranges from 220 to 3200 m over the 130 km length of the basin. The main tributaries are Mari Khola, Lungri Khola, Arung Khola and Jhimruk Khola (Figure 5.16). All major tributaries meet upstream of the Bagasoti gauging station from where the river flows into a wide flood plain.
**Figure 5.15** Location of the West Rapti catchment in Nepal

**Figure 5.16** Location of gauging stations in the West Rapti basin
The climate of the West Rapti basin varies from sub-tropical to cool temperate in the mountainous headwaters. The cultivated areas represent about 16% of the total catchment. Approximately 30% of the cultivated land is irrigated. The lower part of the basin is less mountainous and includes a fertile plain that is heavily cropped. There are many significant diversions of water from the main West Rapti River, mostly between the Bagasoti (103500) and Jalkundi (103600) gauging stations. The water is used for irrigation through government irrigation schemes or locally constructed diversions, as can be seen in Figure 5.17. The competing demands for irrigation water during the dry-season results in this basin being selected as a pilot catchment.

![Figure 5.17 Government irrigation scheme (left) and locally constructed diversion (right) in the West Rapti basin](image_url)

A study by engineering consultants Tahal (2002) has attempted to quantify consumptive water use within the catchment by considering dominant cropping patterns, irrigable areas, current irrigation schemes, and population and livestock distributions throughout the catchment. Preliminary data from this study were used to illustrate the application of the IWRM tool in the West Rapti basin, see Table 5.4.

### Table 5.4 Net consumptive water requirements for sub-catchments of the West Rapti

<table>
<thead>
<tr>
<th>Stn</th>
<th>Area (km²)</th>
<th>Total month consumptive water requirements (m³/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>103270</td>
<td>2.9</td>
<td>Jan 0.2  Feb 0.3  Mar 0.3  Apr 0.2  May 0.2  Jun 1.2  Jul 0.5  Aug 0.7  Sep 0.5  Oct 0.6  Nov 0.4  Dec 0.3</td>
</tr>
<tr>
<td>103300</td>
<td>34.8</td>
<td>Jan 1.7  Feb 3.0  Mar 2.9  Apr 1.9  May 1.9  Jun 14.1  Jul 5.6  Aug 0.8  Sep 5.7  Oct 6.4  Nov 3.6  Dec 2.6</td>
</tr>
<tr>
<td>103330</td>
<td>2.7</td>
<td>Jan 0.1  Feb 0.2  Mar 0.2  Apr 0.2  May 0.2  Jun 1.2  Jul 0.3  Aug 0.1  Sep 0.3  Oct 0.5  Nov 0.3  Dec 0.2</td>
</tr>
<tr>
<td>103395</td>
<td>25.9</td>
<td>Jan 1.2  Feb 1.9  Mar 1.9  Apr 1.3  May 1.5  Jun 11.0  Jul 3.82  Aug 1.02  Sep 4.49  Oct 4.64  Nov 2.49  Dec 1.78</td>
</tr>
<tr>
<td>103500</td>
<td>80.1</td>
<td>Jan 4.1  Feb 6.9  Mar 6.8  Apr 4.7  May 4.9  Jun 33.1  Jul 12.0  Aug 3.4  Sep 13.2  Oct 15.0  Nov 8.2  Dec 5.9</td>
</tr>
<tr>
<td>103600</td>
<td>249.6</td>
<td>Jan 11.6  Feb 21.7  Mar 19.5  Apr 14.3  May 14.8  Jun 110.3  Jul 37.5  Aug 10.6  Sep 41.1  Oct 47.3  Nov 22.2  Dec 14.9</td>
</tr>
</tbody>
</table>

Note: [1] Area is the cumulative irrigated area (km²) upstream of the gauging station.
Table 5.4 clearly shows the Jalkundi (103600) catchment to be the most impacted by water-use, with the majority of the water used between this gauging station and 103500. This area is in the flat and fertile floodplain. The total monthly water requirements were converted to monthly abstraction volumes and entered into the IWRM software as monthly profiles. The impact of this use on the flow regime at the 103600 gauging station can be seen in Figure 5.18. The figure shows that the predicted influenced recession at 103600 gives a good approximation of the observed flow record at this gauging station. Although the abstractions are small during the dry-season, they are a significant proportion of the natural flow during these critical months.

Figure 5.18 Comparison of observed flows, predicted natural influenced flows at Jalkundi

Figure 5.19 compares the predicted and observed mean flows at Jalkundi plus or minus one standard deviation to give an indication of their variability. It can be seen that the predicted influenced recession lies within the envelope of observed flow variability for this catchment. Furthermore, Figure 5.19 suggests that the magnitude of the variability of observed flows during the driest months (April and May) is of a similar order to the difference between the predicted natural and influenced flows. Hence, the observed variability of flows may reflect the year-to-year variability of water use within the catchment, as well as natural variations in climatic conditions and storage behaviour.

The predicted influenced flows during April and May are less than the observed long-term average flows measured at Jalkundi. However, it should be noted that the simulated water-use scenario represents a “theoretical” level of water use, rather than measured data. The Tahal study identified levels of water use based on a number of assumptions regarding population distributions, use per capita, use per head of livestock, crop water requirements for various crop types, lengths of irrigation seasons, irrigation efficiencies etc. Hence, uncertainties associated
with each of these assumptions regarding water use will directly impact on the accuracy of the simulation of influenced flows. The predicted flows must be examined in light of the observed variability of flows at the gauging station, which suggests that significant variations in the low flows do occur. The results shown in Figure 5.19 suggest that water-use during the dry-season may have been over-estimated.

![Figure 5.19 Comparison of observed and predicted flows at Jalkundi (103600)](image)

**Figure 5.19** Comparison of observed and predicted flows at Jalkundi (103600)

### 5.6 Dissemination

The objective of this project was to develop the IWRM software tool to prototype stage and then present the prototype to an audience of practitioners dealing with real water resource issues in the HKH region. The prototype represents a starting point both for demonstrating the functionality of an IWRM and for scoping how such a tool may be further developed and implemented within the region.

Both versions of the prototype IWRM software were thoroughly tested at CEH Wallingford by water practitioners from India and Nepal in December 2002 and various changes were recommended and applied. Two one-day stakeholder workshops were then organised in Kathmandu, Nepal and Shimla, the state capital of Himachal Pradesh in India, on 9 and 13 May 2003, respectively. Water experts from the public and private sector attended the workshops, including policy makers, water managers, planners, regulators, hydropower developers, engineers and university lecturers. Twenty-four people participated in the workshop in Kathmandu, a further 18 attended the Shimla workshop (see Annex 2.1 & 2.2). CEH staff presented the regional recession flow model that was incorporated within the IWRM software before demonstrating, at length, the software itself (see Figure 5.20).
Discussions were held at the end of each workshop to, first, gauge whether such a tool would be useful in the region for managing water resource and, if so, identify how the tool may be further developed to address real-world water resource management issues facing local people. Experts at both workshops expressed a keen interest to develop such software operationally in their respective areas.

Figure 5.20 IWRM stakeholder workshop in Shimla, Himachal Pradesh, 13 May 2003

Currently in Nepal, the Electricity Development Department grants licences to develop hydropower in Nepal and the Nepal Electricity Authority (a government body) also deals with private hydropower schemes. While all formal irrigation schemes are currently constructed by Government agencies in Nepal, many unofficial small-scale diversions are created to supply irrigation water. At present, such abstractions are not managed in a coherent way and, hence, water conflicts may occur during the dry-season, when water users are affected by abstraction regimes upstream. However, the meeting was told that the Water and Energy Commission Secretariat (WECS), who would be responsible for integrated water resources management in Nepal, were in the process of developing a national water plan comprising a regulatory framework and legal statutes governing the management of water. The plan will have a significant impact on how water is managed across Nepal and it was generally considered that the IWRM software presented at the workshop would be very helpful towards its implementation. Although it was acknowledged there would be difficulty in quantifying the hundreds of thousands of “unofficial” abstractions and discharges nationally, there was an urgent need to start an inventory of all artificial influences. It was considered that the licence-site-purpose structure used in the software would be a good model for this.

In Shimla, the workshop was informed that the Irrigation Department of the State Government operates the majority of official irrigation schemes in India. Hence, there has not been a historical need to manage water abstractions across a wide range of users. However, small local schemes do exist and may draw significant water from headwater streams during the dry-season. The State Irrigation Department in conjunction with the State Power Department is consulted
during the process of granting rights to develop hydropower sites. There are a number of
requirements for developers wishing to develop hydropower schemes, which involved
demonstrating that a potential site has sufficient water to make the scheme viable. As
environmental and downstream user rights become more widely considered, there will be an
even greater need for water managers to assess availability during the planning phases of such
projects. Those attending the Shimla workshop thought the software would be very useful for
allocating water resources in the region and avoiding conflicts. Developers and planners agreed
the software would be particularly useful for estimating flows and the impact assessment
aspects of Detailed Project Reports (DPR) for proposed new schemes. However, it was thought
the lack of a single regulatory body to formally monitor and control river flows and issue
licences for abstractions and discharges across all uses would be a barrier to the widespread
implementation of the software in India.

Various possibilities for the further development of the software were considered at both
workshops, including whether the software should be made operational in the pilot basins,
which other catchments would benefit from such software and whether such software should be
developed regionally or on a priority catchment basis. In conclusion, each workshop agreed to
appoint one individual to coordinate the feedback from the workshops and canvas the opinions
of relevant ministries, regulatory bodies and others in order to develop a proposal for further
implementation. To aid them with this activity, the software was installed at the Department of
Hydrology and Meteorology in Nepal and at the Alternate Hydro Energy Centre at the Indian
Institute of Technology in Roorkee. Appropriate training was given to technical support staff at
both organisations to enable them to use the software and demonstrate it to interested parties.

5.7 Conclusions

Water resource managers and practitioners are often faced with the need to estimate the
availability of water in catchments where no historical records exist. The new regional recession
flow models of Chapter 4 provide a relatively reliable and robust means of estimating flows at
ungauged site during the critical dry-season, when competition for water resources is at its
highest. This chapter has shown how those models can be applied operationally in a prototype
IWRM tool for two pilot basins in the Himalaya where, according to local stakeholders, the
management of water resources is becoming a critical issue. The software has also demonstrated
how estimates of natural water availability can be compared to spatially referenced information
on abstractions, discharges and impoundments to determine how much water is actually
available at different locations in a given catchment. It has shown how different “what-if”
scenarios can be applied to assess the impacts on the flow regime of new or existing schemes.
The response of the experts who attended the stakeholder workshops clearly show that such a
tool would be of great benefit to water resources managers in the HKH region. It is particularly
satisfying to see that local practitioners themselves are actively pursuing the options for its
further development.
6 Capacity building


6.1 Introduction

The challenge for sustained economic growth and poverty alleviation in the Hindu Kush – Himalaya (HKH) region is closely associated with the sustainable use of natural resources and better management of the environment. In the case of water, countries need to develop and implement long-term national programmes based on a multi-sectoral approach to water resources management to improve human welfare, ensure more efficient use of scarce water resources, maintain water quality, and provide options for future use.

Within the HKH, there is a recognised lack of institutional capacity to monitor, plan and manage water resources in an effectively and sustainable manner. Many governments have only a limited ability to collect the data and information needed for comprehensive and long-term water resources management. In addition, they have few skilled people, or the funds, equipment and facilities available to do the planning and analysis necessary to guide water resource management decisions. The number of technical specialists remains small because of unattractive salaries and poor career prospects. The development of technical expertise is further compromised by over-reliance on external technical assistance, which does not give sufficient attention to either developing indigenous capabilities or adapting to the constraints of local circumstances. Since water management issues are constantly changing, there is a need for continuing education and training to ensure that organisations have sufficient human resources and technical expertise to meet their operational responsibilities.

The need to provide training to local technicians and hydrologists has been a major component of the HKH FRIEND project since its inception. Within the DFID funded project “UK contribution to the IHP of UNESCO”, CEH Wallingford, in consultation with HKH FRIEND Steering Committee and Secretariat, identified a variety of potential capacity building initiatives. The lack of knowledge and technical expertise in the estimation and management of low flows was considered to be a particular problem area. Similarly, training was thought necessary in the application of GIS in water resources management and methods for water quality monitoring. This chapter details a series of four regional training workshops that were conducted to address the apparent knowledge gap in these areas. It also describes the support provided to one PhD student from the region and the progress he has made with his studies.

6.2 Low flows training workshops

Earlier chapters have described the importance of understanding the low flow behaviour of catchments for the effective management of water resources in the dry-season. However, there are relatively few hydrologists in the region who have the necessary skills and knowledge to assess the availability of water resources and make sound management decisions. A series of training workshops were, therefore, planned, focussing on appropriate low flow estimation methods and their operational application. The aim of the workshops was to strengthen capacity in the region for surface water resources assessment, their planning and management. The workshops were specifically targeted at young, recently qualified technicians or graduate hydrologists who would be able to use and build upon the methods in their daily work and future careers.
Due to circumstances beyond the control of the project, only two of the three planned regional training workshops on Low Flows were conducted. The first workshop was held at the Indian Institute of Technology Roorkee (IIT Roorkee) on 9-13 October, 2001, with the second held at the Bangladesh University of Engineering and Technology (BUET), Dhaka, on 5-9 May 2002. The third workshop, which had been planned for Pakistan in the autumn of 2002, was cancelled because of the political and social tensions in the region and UK Foreign Office advice against unessential travel to the country.

A local organiser was appointed for each workshop in Roorkee and Dhaka and it was their responsibility to invite local participants and to arrange the venue, overnight accommodation and local transport. The travel and subsistence costs of all local participants were met by the project. There were 18 delegates on each course, drawn from a variety organisations and backgrounds including government departments, private consultants and universities (see Annex 3.1 and 3.2). Their knowledge of low flows was quite varied. Some had a reasonable knowledge of low flow estimation techniques and had used them operationally in their work, while others had little or no knowledge at all. Similarly, there were a few who possessed advanced IT and GIS skills and others who had only basic knowledge of computing through their use of simple spreadsheets.

The course contents were finalised in consultation with the local organisers and experts, to ensure they addressed the training needs of participants. Both courses were conducted over five days, with the morning and afternoon sessions typically comprising topical presentations and lectures, interspersed with group exercises and discussions. A one-day field excursion featured in both workshops. For the Roorkee excursion, delegates were taken to the Rishikesh gauging station on the Ganges, to observe streamflow measurement being undertaken by field technicians, and to the irrigation scheme off-take of the Ganges at Haridwar. The Dhaka excursion included a boat trip to observe methods of streamflow measurement on the Padma River (i.e. downstream of the confluence of the Ganges and Brahmaputra). The training courses were led by CEH staff and included contributions from other local and regional experts. Topics covered were divided into the following five main areas:

- The hydrological cycle and flow regimes - an overview of the main hydrological issues in the region, an outline of general hydrological processes, and a summary of basic concepts of hydrometry, hydrological data management, different types of flow regimes and common low flow measures;
- Low flow measures in gauged catchments - a description of the characterisation of flow regimes and the calculation of low flow measures or statistics from historical flow records at gauged sites;
- Low flow estimation at ungauged sites - a description of how low flow measures or statistics may be estimated at ungauged sites using a variety of techniques from the use of local data to regionalisation approaches;
- Regionalisation - an overview of general regionalisation techniques, regionalisation in the HKH;
- Spatial data and catchment characteristics – description of spatial data, GIS and the use of catchment overlays to predict catchment characteristics at ungauged sites for use in regional models.

The principal methods outlined for gauged sites included flow duration curves, low flow frequency curves and the baseflow index. Other low flow measures (e.g. low flow spell duration frequency analysis, runoff accumulation time, etc.) were addressed briefly. For ungauged sites, correlation analysis, transposition and the use of spot current metering were covered, and the concept of regionalisation was more fully detailed. Each delegate was provided with a complete set of course notes and copies of prepared exercises relating to the workshop topics. Supplementary notes from local lecturers supporting their presentations were also provided.
On the final morning of each course, a practical problem, requiring the application of the methods taught during the previous four days for its solution, was posed. In the afternoon delegates were invited to identify the most critical issues for water resources management in the region and explore how these issues might be addressed.

At the end of the workshops, delegates were also asked to appraise the workshop by completing a questionnaire. Most considered that the training was useful and beneficial and relevant to water resource management issues in their respective countries. They were generally satisfied with the content and duration of the workshop and how the material was presented. They found the group projects particularly worthwhile and would have liked more exercises of that type. Several thought the practical project at the end of the workshop was a highlight, enabling them to put the skills they had acquired to practical use. Some participants recommended that the material covered should feature in the curricula of university undergraduate and post-graduate courses so that the methods are taught more widely in the region. It was generally felt that the skills taught would help to strengthen capacity in the region and would be of immediate benefit.

6.3 Regional training course on “Application of Geo-Informatics for Water Resources Management”

Geo-informatics (GIS, Remote Sensing, and GPS) technology is becoming a key tool in decision support systems. GIS is now accepted as a useful tool for assembling water resources information and its analysis. The increasing use of GIS in water resources has broadened the concept of water resources data to include geo-spatial data describing the water resources features with landscape. To help build local capacity in GIS and to keep abreast of recent technical developments, a regional training course on the “Application of Geo-Informatics for Water Resources Management” was organised at ICIMOD in Kathmandu on 17-28 March, 2003. The training was attended by fourteen participants from nine different institutions from India; 1 from Myanmar, 5 from Nepal; and 1 from Pakistan (see Annex 3.3; Figure 6.1). Staff from the MENRIS division of ICIMOD conducted the training.

A training course manual was developed specifically for the two-week course. The manual contains 22 chapters in 10 Sections and covers most of the ArcMap and ArcCatalog utilities of the ArcGIS software. A CD and a book, “GIS for Beginners”, co-authored by the Coordinator of the Database Group, was also distributed to the participants as part of the training. The participants were also introduced to ArcHydro, an extension tool in ArcGIS jointly developed by ESRI and Centre for Research in Water Resources, University of Texas at Austin, USA. The two-week training course focused mainly on the use of GIS in water resources management. Participants were introduced to GIS concepts, to building a geo-spatial database and data models of basins. During the last three days, participants worked in groups on a chosen topic and presented their results during the formal closing session.

In addition to the training course, the participants were informed of the Internet based database system of the RHDC and other HKH FRIEND activities including its website, which can be visited at http://www.hkh-friend.net/. They were also briefed about the other ongoing activities at MENRIS, ICIMOD, such as internet mapping (ICIMOD GIS Portal) and a study on “Glaciers, Glacial Lakes and the identification of Potential Glacial Lake Outburst Floods (GLOF) in the Mountains of the HKH region”.

The training also proved to be fruitful in expanding the FRIEND network in the region. All the participants, especially those from the Bureau of Hydrology, Tibet and Department of Meteorology and Hydrology, Myanmar, expressed their willingness to participate actively in the future RHDC activities. The Department of Meteorology and Hydrology, Myanmar provided the RHDC with its hydrological and meteorological network metadata during the training.
On March 28 2003, the training programme formally closed with a brief concluding ceremony at which the participants expressed their view that the training was very useful and all were grateful for the opportunity to attend.

**Figure 6.1** Participants of the Regional Training Course on “Application of Geo-Informatics for Water Resources Management”, Kathmandu 17-28 March 2003.

### 6.4 Regional training workshop on “Capacity Building for Monitoring River Quality in the Hindu-Kush Himalayan Region”

The HKH FRIEND regional training on “Capacity Building for Monitoring of River Quality in the Hindu-Kush Himalayan Region” was held in Dhulikhel, Nepal from 10-14 May 2003. The training was organized jointly by the Water Quality Group of HKH FRIEND, ICIMOD, and Kathmandu University in cooperation with the German IHP/OHP National Committee, the Federal Institute of Hydrology (BfG), Germany, CEH Wallingford, and UNESCO. Sixteen participants from various government and non-government organizations in Bangladesh, India, Nepal and Pakistan participated in the training. A list of workshop participants is given in Annex 3.4. Lecturers came from Austria, Germany, Nepal and the UK.

The training was a follow-up to an earlier water quality workshop held in Islamabad, Pakistan in May 2001, which had looked into the chemical aspects of water quality monitoring. The participants had drawn attention to the lack of trained manpower in the region to assess the ecological status of rivers and the need for standardised sampling and data processing. To address these concerns and fill the knowledge gap in biological monitoring, the week-long training workshop in Dhulikhel focussed on biological techniques (rapid bio-assessment) for monitoring the water quality for surface water bodies. The focus was on organic pollution, biological indicators and methods to pre-evaluate the ecological status of rivers in the HKH region. The training included lectures as well as field visits, lab tests and demonstrations.

During the first technical session, the rapid field assessment technique was introduced and such topics as multi habitat sampling and benthic macro-invertebrates were discussed. The technique was demonstrated at a stream near Banepa, with the trainees involved in sampling (Figure 6.2). The samples were taken to the laboratory and later analysed to determine the water quality of the stream.
Figure 6.2 Water quality sampling near Banepa and subsequent laboratory analysis

On subsequent days, the trainees were taken to two different sites and the water qualities of the sites were analyzed using the rapid field bio-assessment technique. Training was provided on diatoms and their use as biological indicators, including demonstrations of procedures for sampling diatoms and preparation of diatom slides. The trainees also worked in the laboratory at Chandeswari Kola on the identification of the macro invertebrates sampled on Day 1 and applied the Nepbios (Nepalese Biotic Score) technique to determine the river water quality. The results from this were in general agreement with those obtained by applying the rapid field assessment technique. Other topics discussed during the course included the European Water Directive and its possible applications in the HKH region and the activities of HKH FRIEND and opportunities for continued networking.

The participants also presented their views on the training and made some recommendations. The participants were keen to implement the technique of bio-monitoring in their respective countries and suggested that HKH FRIEND should help to initiate these activities. The trainees suggested a follow-up training course focussing more on the identification of the macro-invertebrates found in the HKH region, and suggested the initiation of small-scale water quality projects to produce water quality maps. These water quality maps could then be merged to form a master water quality map for the region. For follow up and continued networking, it was recommended that a newsletter be published/circulated every four months via e-mail and made available on the HKH FRIEND web-site.

At the concluding session in Kathmandu University, participants presented and discussed the findings of the rapid field bio-assessment. It was agreed that the training had built up the much-needed capacity of sixteen participants from four regional countries. This new knowledge on biological monitoring will enable the participants to make a rapid assessment of the water quality of rivers. It was expected that they would share the knowledge in their respective institutions and countries to further build capacity and to improve understanding of the deteriorating river water quality in the region and its mitigation.

6.5 Support to a PhD student from the region

To further strengthen the hydrological capacity of the region, a young Nepalese scientist was sponsored to complete a PhD as an extra-mural student at the University of Birmingham, UK. A suitable candidate was identified from the Department of Hydrology and Meteorology (DHM) in Kathmandu, who undertook the study on a part-time basis while still working at DHM. All fees and costs relating to the PhD, such as registration and tuition fees, travel and subsistence costs for study visits to the UK and a visit by his university tutor to Nepal were met by the project.
The research focuses on the regional estimation of flow regimes in Himalayan catchments, an area in which there has been little previous work. Those studies which have been undertaken have either considered Nepal as a single homogeneous unit or subjectively divided the country into regions based upon physiographic or administrative zones. None have fully accounted for the complexity of river flows in space or time and there was therefore a need to investigate flow seasonality in more detail. This research seeks to fill the gaps by linking spatial and temporal variations in flow and precipitations regimes across Nepal, using data from 28 catchments and 222 precipitation stations. The PhD thesis is due to be submitted early in 2004.

Within the study, river flow regimes have been characterised according to their spatial and temporal behaviour. The results show that flow regime shape and magnitude are independent of each other. Well-defined, geographical regions of flow regime dominance are not apparent, except in the west and central Middle Mountains. Thus, previous regionalization studies to predict runoff in ungauged basins, where data have been pooled for large administrative or physiographic zones, are likely to be inaccurate due to this high within-region variability. To strengthen these inferences, the study also investigated the spatial and temporal variation in precipitation regimes across the country. The precipitation regime shape and magnitude were found to be similarly independent, indicating that the key controls upon spatial patterns in Nepalese precipitation are length and timing of the summer monsoon. The stability of the annual precipitation regime increases from south to north and from east to west, with topography exerting a greater influence on the precipitation regime than the summer monsoon. The effect of large-scale climatological circulation phenomena on precipitation across Nepal has also been investigated and it has been found that El Niño- Southern Oscillation (ENSO) behaviour is significant in influencing the precipitation regime over Nepal. The study has further analysed the links between precipitation and flow regimes. The annual flow regimes of snow-affected basins were found to be less sensitive to annual precipitation regimes than those without snow area. A better understanding of the flow-precipitation regime link could be useful for predicting flows of ungauged basins. The potential impact of climate change on precipitation and flow regimes across Nepal is presently being investigated.
7 Conclusions

H.G. Rees

7.1 Review of activity

The activities described in this report have added considerable impetus to HKH FRIEND. They also represent a substantial and highly effective contribution by the United Kingdom towards the implementation of the UNESCO IHP in the HKH region. The achievements of the three activities supported by DFID are reviewed as follows:

- **Development of the FRIEND HKH Regional Hydrological Data Centre**
  
  Political problems and sensitivities over the sharing of hydrological data continue to beset the HKH region. Yet, it is a part of the world where, due to the sparseness of national hydrometeorological monitoring networks, the sharing of data would result in substantial improvements to methods of assessing and managing water resources. In formally establishing a strategy for the Regional Hydrological Data Centre (RHDC) and setting a clear direction for its future implementation and development, this project has made significant progress towards facilitating better hydrological analysis and improved water management in the region. The successful appointment of the first two Focal Nodal Agencies in Nepal and Pakistan has been a vitally important first step in the implementation of the RHDC and should encourage other participating countries to establish their own agencies and contribute hydrological information and data. The future success of the RHDC and, indeed, the whole of HKH FRIEND will rely heavily on this network of Focal Nodal Agencies and the data it will supply. At the same time, it will be incumbent upon participants of the HKH FRIEND project to demonstrate the benefits of data exchange by delivering high quality science and outputs that enable the effective management of water resources. To-date, the time-series of hydrological and meteorological data held on the RHDC represents a small fraction of the data that is potentially available. Accordingly, the few regional studies that have been possible within HKH FRIEND, such as those outlined in Chapter 4, have been limited in scope. Acknowledging that obtaining and centrally storing data is a problem that will not be resolved in the short-term, the RHDC has proceeded to collate a metadata catalogue of the hydrological data that exists in the region. By advising on the availability of data and the organisations responsible for it, the catalogue will be of great use to the HKH FRIEND project or to anyone having an interest in Himalayan hydrology. Access to the catalogue is provided through an accessible and easy to use WWW portal. The limited time-series data that is available is similarly accessed via the portal. It is hoped that this facility will not only promote hydrological research but will also encourage national hydrometeorological agencies in the region to contribute data and information to the RHDC.

- **Development of regional low flow estimation methods for the HKH region**
  
  The regional hydrological model for estimating dry-season flows, described in Chapter 4, illustrates what can be achieved with a relatively small amount of data from more than one country – in this case, with river flow data from as few as 11 Indian and 29 Nepalese catchments. Post-monsoon flow recessions were shown to behave consistently from year to year across the region meaning that an estimate of the long-term average annual recession curve at a location would provide a good approximation of the actual dry-season flows. Statistically robust models were obtained for defining the three key-parameters (To, Qo and k) required to describe the average annual recession curve at any location in the study area.
Comparisons between the long-term recession parameters of the regional models and those estimated from a spot-gauging campaign in two separate “test” catchments showed general agreement. The analysis suggested that the uncertainty in the recessions estimated from the models was approximately equivalent to a four- to six-year programme of five spot-gaugings per year. The models for estimating average recession flow are a significant advance over the regional hydrological models that have previously been developed (e.g. WECS, 1990; Singh, 2001), as they are able to describe the temporal sequence of flows during the critical dry-season.

The application of the regional recession flow model was demonstrated in the Uhl and West Rapti river basins in India and Nepal, using an adapted prototype version of the Low Flows 2000 integrated water resources management software. As explained in Chapter 5, the software enables the natural average annual recession flow to be determined along any river reach in either basin. It does so automatically, by referring to an especially digitised river network to define the catchment boundary upstream of the selected location and then overlays this boundary onto a 1-km elevation grid to determine the pertinent parameters of the recession model. The software contains a database that is designed to geographically reference and store details of the artificial influences occurring in either basin. The types of influences that can be represented are surface water abstraction, groundwater abstractions, discharges and reservoirs or impoundments. A monthly profile of water use may be ascribed to each artificial influence registered on the database. Innovatively in this project, a Crop Water Requirement tool was developed and incorporated within the software to estimate the monthly abstractions required to irrigate particular crops over specified areas. The tool uses FAO guidelines to calculate the varying irrigation water demands over the growing season for typical crops in the HKH.

For any location, the prototype IWRM software determines the upstream catchment boundary, identifies the artificial influences within the catchment and calculates both the natural and artificially influenced recession curve. This gives an immediate indication of how the natural flow regime of a catchment is influenced by the human activity upstream. Various “what-if” scenarios can be applied to the artificial influence data to assess the effect of changes in water demand. For example, what effect does doubling the surface water abstraction from point A have on the river flows downstream at point B?

The prototype software was demonstrated to 42 water practitioners at two stakeholder workshops in Kathmandu and Shimla (India) in May 2003. In Nepal, workshop participants suggested the tool would be very helpful for implementing the new national water plan that is being prepared by the Water and Energy Commission Secretariat. Participants of the Shimla workshop thought that the software would help with the equitable allocation of water resources and be of particular use with the hydrological assessment aspects of Detailed Project Reports for new water management schemes. Encouragingly both groups expressed a keen interest to develop the software further in their respective countries and have appointed representatives to consult with relevant ministries, regulatory bodies and others in order to develop a proposal for the operational implementation of the software. The response clearly shows there is a pressing need for such tools in the region. Moreover, this project has confirmed that it is possible to develop robust hydrological models for assessing river flows at ungauged sites in the HKH and has shown how such models can be applied successfully to provide powerful tools for improved water resources management.

- Training and Capacity Building

Due to the recognised lack of institutional capacity within the region to monitor, plan and manage water resources effectively, training and skills transfer has always been a priority of the HKH FRIEND project. Chapter 6 described four training workshops in Bangladesh, India or Nepal that were supported within this project. Training was provided to a total of
66 local hydrologists or technicians on the topics of Low Flows, River Quality Monitoring or the Application of Geo-Informatics in Water Resources Management. Participant feedback indicated that all courses were of practical use and would help strengthen capacity in the region. The format of the week-long courses (two weeks for the Geo-Informatics course), where classroom lectures were interspersed with practical group exercises and field excursions, proved very popular and it was suggested that more courses of this type be held in the future. Several participants recommended that the material covered should feature in curricula of university undergraduate and post-graduate courses. The comments made by course participants have influenced the future activity proposed in Section 7.2. The project also sponsored a young hydrologist from the Department of Hydrology and Meteorology in Nepal to conduct research as an extra-mural PhD student at the University of Birmingham. Good progress has been made and the PhD is due for completion early in 2004.

7.2 Outlook for the HKH FRIEND project

The work presented in this report has contributed to three of the six research groups that comprise HKH FRIEND: Database, Low Flows and Water Quality. There has also been good progress with other HKH FRIEND groups, which is outside the scope of this report. The Floods group, for example, has been actively promoting a Regional Flood Forecasting System for the HKH region and, with backing from the US Agency for International Development and Office of Foreign Disaster Assistance (USAID/OFDS), have developed an Action Plan is association with the WMO. The aim of the project is to minimize loss of lives by reducing flood vulnerability in the region. Another on-going initiative of the Flood group is the development of a map of flood risk vulnerability in the HKH. The work is being conducted by ICIMOD, with the support of by UNESCO, and was due for completion in November 2003. For the Snow and Glacier group, the Glacier Mass Balance Training in India in September 2002 represented the first step towards the development of a regional network for glacier mass balance monitoring the sensitivity of Himalayan glaciers to climate change. A manual is to be produced by the group on mass balance measurement techniques. CEH is an active member of this group and is presently collaborating with other participants on a DFID Knowledge and Research funded project into the impact of deglaciation on the water resources of the Himalaya and the consequences for downstream communities.

This high level of activity and enthusiasm for international collaboration are all indicative of the success of HKH FRIEND. Many participants actively contribute to research, while many more benefit directly from the training provided. This bodes very well for the future of the project and, ultimately, for the goal of improved water management in the region.

However, it is evident that there is still much scope for improving hydrological research in the region and for developing tools for sustainable water resources management and for flood and drought mitigation. There is a common perception that climate change is occurring faster in high mountain areas than other parts of the world. The need to conduct further research on how variations in climate and hydrological regimes impact upon the environment and the lives of peoples in Himalayan river basins is, therefore, becoming increasingly important. Following discussions with local hydrologists, the following four areas were identified, and agreed, as future priorities for the HKH FRIEND project:

- Establishment of a Regional Centre for Climate Impact Studies (RECCIS)

There is much evidence to show that mountain environments are particularly sensitive to climate variability. It is proposed that a regional centre be established, under the auspices of HKH FRIEND, to study how variations in climate and hydrological regimes impact upon the environment and the lives of peoples in Himalayan river basins. The Centre would provide a focal point for scientists throughout the region to meet to exchange knowledge.
and expertise on regional climate issues. It would seek to advance research on such issues as the impacts of deglaciation on water resources, effects of changes in rainfall distribution and potential changes to the frequency and spatial distribution of extreme hydrological events, through a coordinated programme of research activity.

- **Training and capacity building**
  
The recommendations of participants and experience gained from previous HKH training has been considered in a review of future training needs. This will place a greater emphasis on the dissemination of training to ensure maximum potential impact in terms of the numbers of people reached. It will focus on:
  
  - Developing self-help training material, so that staff can extend their knowledge and expertise whilst spreading their study over weeks or months while not interfering with their normal day-to-day activities;
  
  - Developing of training courses for trainers, to educate those responsible for teaching hydrology on new methods used in hydrological design and water resources assessment;
  
  - Development of university curricula, working alongside lecturers and academic staff of universities and colleges in the HKH to redefine and/or design the hydrology modules of undergraduate and post-graduate courses
  
  - Support to post-graduate studies, to provide assistance to students undertaking post-graduate research on relevant topics at universities in the HKH;
  
  - Dissemination of hydrological research and science, adding “value” to scientific research by publicising the results in an appropriate manner to target users, and encouraging uptake in projects and increased awareness by other organisations.

  The RECCIS would act as a regional centre for these activities. It will encourage the mobility and exchange of scientists within the region, facilitating working visits of up to three months to other research organisations in different countries of the region. It was felt that this would help foster international cooperation both between organisations and between individuals in the region.

- **Tools for improved water resources management**

  Following on from the activity described in Chapters 4 and 5, it has been suggested that a hydrological tool-box be established, which would enable appropriate hydrological models to be identified, developed and applied at different locations in the HKH region. The prototype IWRM software developed in this project could become a component of the tool-box. To demonstrate their effectiveness, tool-box components should be tested in contrasting river basins in Bangladesh, Bhutan, China, India, Nepal or Pakistan.

- **Development of the Regional Hydrological Data Centre**

  The next phase of the development of the RHDC will be devoted to extending its data coverage and strengthening the data network. The RHDC aims to develop the capacity of the participatory institutions in the preparation of databases at the regional and country level. To provide a source of funding to sustain its activities in the long-term, the RHDC will attempt to generate “value-added” products that will be commercially available and more useful to a wide range of users. The RHDC will also seek to conduct a variety of research activities, including studies on data model development, data harmonisation and new applications based on emerging technologies (e.g. internet technology, web-based GIS, visualisation). Such research is considered necessary if the RHDC is to establish itself as a leading authority on database management in the region.

These ideas and proposals were put to the HKH FRIEND Steering Committee at their last meeting in May 2003 and were endorsed as future priorities for the project, provided
appropriate funding can be secured. CEH are optimistic that such funding will be forthcoming to support the continuation of the important work of HKH FRIEND in the region.

Nevertheless, this DFID funded project has clearly bolstered the capacity for hydrological research and sustainable water management in the HKH region. This has been achieved by providing improved access to regional hydrometeorological data, by demonstrating the benefits of integrated water resources management and by providing training in contemporary methods to young technicians and scientists. This work is contributing to the UK Government goal of poverty elimination (DFID, 1997). It will encourage local authorities and agencies to improve their management of water resources to ensure a reliable and equitable supply of clean water for drinking and cooking, food production, power generation and industry, while also encouraging the safe and proper disposal of industrial effluent and human waste. The quality of water will also be enhanced bringing added benefits to human health and the environment.
8 References


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Annex 1.1

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Hotel Himalaya, Kathmandu, 9 May, 2003

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Implementation of an Integrated Water Resources Management tools in the Himalayas: participants in the Shimla workshop

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9-13 October, 2001

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Annex 3.3

Regional Training Course on “Application of Geo-Informatics for Water Resources Management”

ICIMOD, Kathmandu, March 17-28, 2003

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Regional Training Workshop on “Capacity Building for Monitoring River Quality in the Hindu-Kush Himalayan Region”

Dhulikhel, Nepal, May 10-14, 2003

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