Chapter- 6

Synthesis and Future Perspectives

The study described in this thesis is an investigation on the chemical and physical erosion process in the Ganga basin on different spatial and temporal scales. These sub-basins include the Himalayan, the plain and the peninsular drainages of the Ganga basin. Physical erosion processes have been studied on spatial scales of individual river basins of the Ganga system. The goals were to quantify the supply of sediments from different litho-units of the Ganga drainage to the Ganga plain and to determine variability in physical erosion rates among the various river basins and its causes. These studies have direct relevance of regional tectonics and geomorphology. Chemical erosion studies have been made on a wider spatial scale, the three sub-basins of the Ganga drainage, the Himalaya, the Gangetic plain and peninsular basins. The focus of these studies has been to quantify the chemical erosion rates in these sub-basins and to assess the role of the Gangetic plain and peninsular basins in contributing to the chemistry of mainstream Ganga and its implications to determination of silicate erosion rates in the Ganga basin and elemental fluxes to the Bay of Bengal. In addition, work also has been carried out as a part of the thesis to explore the application of chemical composition of particulate phases in the Ganga to derive silicate erosion rates.

The findings of this work have been integrated with those reported for another major Himalayan river basin, the Brahmaputra, to obtain a synoptic view of contemporary erosion processes in the Himalaya.

6.1 Studies on Physical Erosion in the Ganga basin.

Bank sediments from the Ganga and its major tributaries in the Himalaya, the plain and peninsular basin were collected and analyzed for their major elemental composition and Sr, Nd and isotope systematics ($^{87}Sr/^{86}Sr$ and ε_{Nd}). These data, in conjunction with those available in the literature for the source rocks from the Himalaya, Deccan and peninsular sub-basins have been used to quantify major lithounits supplying sediments to the Ganga plain and relative contribution of major tributaries to the sediment budget of the Ganga. The results show that the Higher Himalaya Crystallines (HHC) is the dominant source of sediments to the Ganga in the plain contributing in excess of two thirds of the total sediments. This work has also brought out the minor role of peninsular rivers in the supply of sediments to the Ganga at its out flow. Among the sub-basins of the Ganga, Gandak dominates the sediment budget contributing about half of the sediments at Rajmahal near the Ganga outflow. The present day physical erosion rates among the Himalayan sub-basins of the Ganga vary between 0.5±0.25 to 6±3 mm yr^{-1} with the highest value for the Gandak basin. The intense erosion rates over the Gandak basin is attributed to combined effects of intense rainfall in its head waters and high relief. Results obtained on the erosion rates from this study along with those available in literature for the Brahmaputra and the Indus show that within the HH, there are "hotspots" of very rapid physical erosion, with rates varying from 6 to 14 mm yr^{-1} compared to typical rates of 1-2 mm yr^{-1}. These regions are the gorges of the Brahmaputra (Eastern syntaxis), the Indus (Western syntaxis) and the Gandak. These regions undergo mechanical erosion quite disproportionate to their aerial coverage and contribute ~8% of global riverine sediment flux to the oceans.

6.2 Studies of Chemical erosion in the Ganga river system:

The emphasis of the work on this topic was to determine (i) chemical erosion rates in the Gangetic plain and peninsular sub-basins of the Ganga drainage and their impact on the water chemistry of the Ganga and material transfer to the Bay of Bengal and (ii) silicate erosion rates in the Himalayan tributaries of the Ganga and their Ca and Sr budgets. These goals were achieved through measurements of major ions, Sr and $^{87}Sr/^{86}Sr$ in various rivers the Ganga system draining through Himalaya, the Gangetic plain and peninsular basin. The results show that sum of major cation erosion rates, a measure of chemical erosion rates of the basins, on average is ~2 times higher in the Himalayan sub-basin of the Ganga compared to that in its plain and peninsular sub-basins. The Ganga plain and the peninsular drainages, however contribute significantly to the major ion and Sr budgets of the Ganga at its outflow

(Rajmahal) because of their large aerial coverage ~80% of the Ganga basin. For example, the Yamuna supplies most of Na and about half of Mg and Sr and ^{87}Sr to the Ganga at its outflow. The results bring out the dominant role of the plain and peninsular sub-basins of the Ganga in determining the elemental budgets of the mainstream Ganga. The study also shows that the Gomti and the Yamuna draining the plain and peninsular sub-basins of the Ganga are characterized by high Na erosion as a result of solution of sodium salts from alkaline and saline soils in their drainages. The supply of Na from these soils can contribute to uncertainties in the estimation of silicate Na component in these rivers and hence to the application of Na as an index of silicate erosion in their basins and therefore in the Ganga downstream of Kanpur.

The role of calcite precipitation in determining Ca and Sr budgets of the Ganga system river has been a topic of study among geochemists. An attempt to quantify the magnitude of this process in the Ganga headwaters and its Himalayan tributaries was made through measurements of $^{87}Sr/^{86}Sr$ and Ca/Sr in them and using a two end member mixing model for carbonate and silicate rocks of the Himalaya. Results show that about three fourths of Ca is removed from the Ghaghra and the Gandak waters by precipitation whereas in the headwaters of the Ganga and the Kosi, there is no measurable loss of Ca via precipitation. Such precipitation of carbonates in the Ganga plain may be an important mechanism for the formation of 'Kankar' which occur widely in the region. Further, the precipitation of calcite would lead to underestimation of Sr contribution from carbonates, calculated based on dissolved Ca abundance in rivers.

6.3 Studies on Sediment Geochemistry of the Ganga Basin

Measurements of chemical composition of bank sediments, their fine fraction and suspended matter from the Ganga system rivers were carried out to assess the intensities of chemical erosion these sediments have undergone and their utility to estimate of silicate weathering rates in the basin. Comparison of chemical index of alteration (CIA/CIA*) a measure of the intensity of chemical erosion of these sediments relative to that of source rocks (granites/gneisses) of Higher and Lesser Himalaya demonstrate that the bank sediments of the Ganga and its tributaries have not been subjected to any measurable chemical weathering. This is in contrast to the suspended matter and <4μm fraction of bank sediments which show significant chemical weathering. The loss of silicate derived elements (Na, Ca and K) from the suspended matter relative to bank sediments along with reported values for suspended load annual flux has been used to determine silicate weathering fluxes of these elements. These calculations show that for Ca and K, the sediment based fluxes overlap within errors with those based on water composition data, however for Na the sediment derived flux is about twice that estimated from water data. The cause for this discrepancy is unclear, but can be due to limited spatial and temporal coverage in sediment sampling.

Particulate organic carbon (POC) forms a minor component of the Ganga sediments. The POC flux from the Ganga ~2% of the global riverine POC supply to the world oceans. Much of POC in the Ganga is carried in its fine fraction. The sequestration rate of CO_2 by silicate weathering in the Ganga basin and the flux of organic carbon are of similar magnitude and suggest that together these two processes can be an important sink for global carbon budget. In contrast to the particulate organic carbon the flux of particulate inorganic carbon transported by the Ganga forms only ~0.3% of the depositional flux of inorganic carbon in the Bay of Bengal

6.4 Future Perspectives

Research carried out as a part of this thesis has addressed to details of physical and chemical erosion processes in the central Himalaya and its regional and global implications. There are, however, some areas related to this thesis research which need further work. These include

(i) This work demonstrated the importance of the Gandak basin as a "hotspot" for physical erosion. The results though showed that the physical erosion rate in the Gandak basin is much higher than that in other sub-basins of the Ganga, there is a need to better constrain the erosion rate estimates by reducing uncertainties. More detailed sampling, both spatially and temporally of both bank and suspended sediments and analyses of their chemical and isotopic composition are needed to obtain more precise estimates of spatial variability in physical erosion of the Ganga basin.

(ii) The measurements of the Sr and Nd isotopes made in this study showed that the isotope composition of sediments from the Ganga mainstream and some of its tributaries (e.g. the Ghaghra) overlap within errors. This limits the application of these isotope systems to estimate the sediment contribution from such tributaries to the Ganga plain. In such cases it would be worthwhile to explore the applications of other isotope systems (Os, Hf) to determine sediment contribution.

(iii) The role of saline/alkaline soils as an important source of Na to the Ganga in the plain is born out from this study. Further work related to the nature (in terms of chemical composition) and fluxes from this source is needed to better understand and quantify its impact on the application of Na as a proxy of silicate weathering in the Ganga basin.

(iv) It is shown that silicate cation erosion rates can be derived based on chemical composition of suspended matter and bank sediments. However, to understand the factors contributing to discrepancy in the erosion estimates for Na based on sediment and water data need further work. Studies on the role of suspended matter input from peninsular sources, spatial and temporal variations in chemistry of suspended matter, bank sediments and river water at the Ganga outflow need to be conducted to resolve this issue. Once the cause of discrepancy is sorted out, chemical composition of sediment cores can be used to obtain paleosilicate erosion rates.