Critical zone: an emerging research area for sustainability

Paras R. Pujari, V. Jain, V. Singh, K. Sreelash, S. Dhyani, M. Nema, P. Verma, R. Kumar, S. Jain and M. Sekhar

In the era of Anthropocene, characterized by a dramatic increase in anthropogenic pressure, global changes are challenging the capacity of planet Earth to sustain the development of human societies in the long term. In the past two decades, this concern has fostered worldwide efforts to develop integrated studies of the 'critical zone' (CZ), the outer skin of the Earth, extending from the canopy top to the bottom of the aquifer, hosting the continental biosphere and providing basic human needs such as water, food, energy and ecosystem services[1]. Environmental processes within the CZ, such as energy and mass exchange, formation of soil, streamflow and evolution of landscape are critical to sustain biodiversity as well as humanity[2,3]. However, with rapid socio-economic development, the CZ is subjected to increasing stress from anthropogenic forcings such as the growth in human and livestock populations, increase in land use, global environmental changes, and expanding consumption patterns[4]. The expanding needs for sustainable development call for understanding, predicting and managing the complexity as well as dynamics within the CZ and to study its feedback with other compartments of the environmental systems[5,6]. The main challenge faced by the CZ research is to integrate effectively the multiple disciplines at stake, from geosciences, biological sciences, ecology, hydrology, soil science to social sciences, working within a wide range of temporal and spatial scales[7,8]. The interdisciplinary and multiscale study of terrestrial ecosystem processes can be best addressed by critical zone observatories (CZOs), where domain experts across different disciplines study various aspects of the CZ. This will lead to holistic understanding of complex systems[8].

CZOs are distributed in various climatic, geologic and human contexts. Currently, most of CZOs are located in temperate regions. Each CZO is extensively characterized and a wide range of variables are monitored on the long term to understand the processes involved in the response of CZ to changing external forcings. These CZOs, and the scientific communities involved, are growingly interconnected, creating opportunities for inter-comparison and improving the generality of the findings. The US National Science Foundation funded the first three CZOs. This was followed by similar efforts in Europe. It led to four Terrestrial Environmental Observatories – 4 nos (TERENO) in Germany in 2008 and the European Union's four CZOs launched by the Soil Transformation in European Catchments (SoilTrEC) in 2009.

Tropical countries host only a handful of CZOs, even though it is acknowledged that understanding the impact of global changes in the tropics is of utmost importance for climate feedbacks, food production, biodiversity, etc. India is characterized by different climatic, tectonic and lithological settings. There is potential for setting up CZOs in different regions so that differences and commonalities in the behaviour of the catchment can be studied by integrating different disciplines (geology, geophysics, soil science, geochemistry, terrestrial biology, social science, hydrogeology)[9]. At present, several institutions have initiated efforts in this direction and CZOs have been developed in different climatic and lithologic gradients (Figure 1). There is a need to bring all these institutions under a single umbrella of Indian CZOs and share the experiences. This will provide the opportunity to examine at the environmental processes in different climatic and lithologic gradients and draw inferences.

At present, the existing CZOs only cover the Indo-Gangetic Plain, Western Himalayas, the Western Ghats and basaltic terrains in Peninsular India. Regions like the Eastern Himalaya, coastal, delta and islands can be considered in future to develop CZOs. This will enable comparison of the environmental processes in different climatic, typological settings.

The CZO network can be developed with the following objectives: (1) Understanding of the science of the CZ with focus on elucidating the underlying physical, chemical, biological, geological, hydrological, ecological and geomorphological processes, and feedbacks/interactions in various litho-climatic and

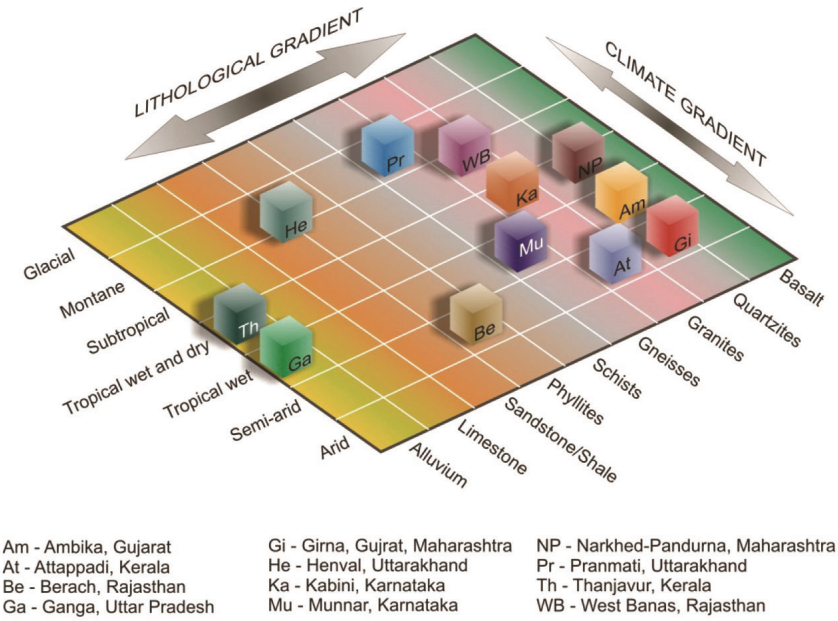

Figure 1. Indian critical zone observatories at different climatic and lithologic gradients.

morpho-climatic/tectonic zones. (2) Developing mathematical and physical models of the functioning of a CZO as a living laboratory for the assessment of anticipated future climatic, anthropogenic and geogenic stresses on terrestrial and aquatic ecosystems, and help plan strategies for sustainable development.

However, there are several challenges in achieving these goals and some of them are listed below:

- Quantitative assessment of interaction of biotic and abiotic factors in the development of CZs. Estimation of the rates and fluxes associated with various physical, chemical, biological (nutrient pathways and their transport), geological, hydrological, ecological and anthropogenic processes with respect to time and space, and modelling the interaction among these processes vis-à-vis the impact of agriculture and urban development.
- Assessment of spatio-temporal variability and dynamics of energy, mechanical stresses, water, sediment and elemental budgets in various ecosystems, and estimation of human impact on them.
- Development of generic/community modelling framework for intercomparison between CZOs across the country and developing linkages between bio-physical and socio-economic indicators.
- Impact of extreme events on CZ processes, and interactions and estimation of tipping points of CZ due to both extreme events and anthropogenic activities using long-term observations.

There is a strong need to develop a long-term programme on CZ by bringing together different institutions under a single umbrella, so that there is better synergy of expertise to develop the CZ science further. Such a network will not only allow us to address local pressing issues, but will also provide invaluable insights to the scientific community to understand the functioning of CZ at the global scale. There is a need to devise a protocol for the measurement of different parameters to facilitate drawing inferences on the impact of natural and anthropogenic stresses in different agro-climatic regions of the country. It is evident that there are other areas (islands, coastal regions, deltas, the Eastern Ghats and Eastern Himalaya) which can be considered in future to set up CZOs.

It is expected that the multidisciplinary CZO programme will provide fundamental understanding to achieve sustainability in the uncertain scenario of climate change and anthropogenic impacts. The output from the CZO programme will provide basic data, knowledge and process models to achieve sustainability in the current challenging time of Anthropocene.

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Paras R. Pujari, S. Dhyani, P. Verma and R. Kumar are in the CSIR-National Environmental Engineering Research Institute, Nagpur 440 020, India; V. Jain is in the Department of Earth Sciences, Indian Institute of Technology, Gandhinagar 382 355, India; V. Singh is in the Department of Geology, Delhi University, New Delhi 110 007, India; K. Sreelash is in the National Centre for Earth Science Studies, Thiruvananthapuram 695 011, India; M. Nema and S. Jain are in the National Institute of Hydrology, Roorkee 247 667, India; M. Sekhar is in the Indian Institute of Sciences, Bengaluru 560 012, India.*
**e-mail: pr_pujari@neeri.res.in*