On satellite geoidal mapping over the Elan Bank, Antarctica

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Satellite geoidal data over the Elan Bank region in Antarctica could be demarcated with the surroundings and confirmed as continental lithosphere. It has been observed that the satellite geoidal map can well demarcate the continental margin region near the Indian coastal region using high-resolution geoid/gravity data. This also helps determine the nature of the lithospheric plate over the Elan Bank. A large portion of land got detached from the Indian plate during the transition processes between the continental and oceanic crust that were originally created by rifting. Satellite geoidal mapping is a comparatively new technique for crust delineation, offshore exploration and tectonics-related studies.

Keywords: Continental crust, geoidal mapping, lithospheric plate, satellite data.

SEVERAL tectonic and oceanographic processes have taken place around India and Antarctica since the Cretaceous, e.g. seafloor splitting, subduction, continental/oceanic margin generation, offshore sedimentary basin generation, etc. Offshore sedimentary basins and geological structures surrounding India and Antarctica have not been explored sufficiently. Seasat altimeter data were utilized by Brennecke and Lelgemann[1] for the exploration of offshore geological structures and passive/active margins in the Atlantic Ocean. Digital images have been prepared from the combined oceanic and continental datasets by Haxby *et al.*[2] to specify their usages in tectonic studies. Gradient methods have been utilized by Sandwell and McAdoo[3] for the analysis of geoid and gravity information. Rapp[4] has developed a method for the prediction of gravity using spherical harmonic coefficients up to and above degree and order 30. Later, a similar method was utilized for the removal of deeper earth effects in geoid generation and gravity modelling.

Thus, satellite altimeter is a new and emerging tool in marine geophysics and geology. Satellite altimeter-derived gravity uses mass of water as a natural gravimeter. The water bulges over mass concentrations, e.g. shallow high-density basement features and is depressed over thick, low-density sediments. Since the satellite altimeter can detect these surface bulges and depressions accurately, which are related to subsurface anomalies, it can provide information for lateral density variation inside the earth (a key factor in oceanographic features identification, oil exploration, etc.). The whole procedure as such is known as 'satellite gravity method'. In case of the Eastern Continental Margin of India (ECMI), two different T_c (elastic thickness) values were obtained for the southern and northern margins, which indicates transform- and rift-type margins respectively[5]. Elan Bank is a micro-continent, presently lying on the west margin of the Kerguelen Plateau in the southern Indian Ocean. It got detached from the ECMI at around 120 Ma. Thus, ECMI had witnessed two continental break-ups in the early stages of the eastern Gondwana splitting. During the process, the Ocean had experienced three major phases of seafloor spreading: it initially moved in the NW–SE direction, then drifted to N–S direction and finally is continuing in the NE–SW direction[6]. The lithospheric plates (Indian, Australian and Antarctic) in the Indian Ocean were reorganized at three geological ages in the past. The oceanic lithosphere in the

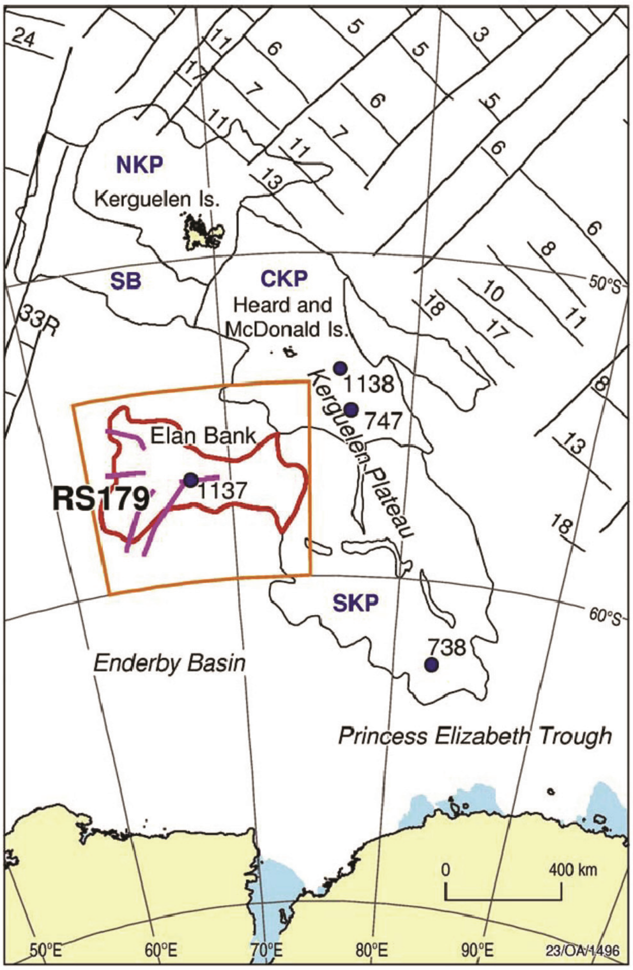

Figure 1. Location of Elan Bank (delineated in red), Antartica, in the Indian Ocean, including MCS coverage (RS179, pink lines) and ODP Site 1137. SB, Skiff Bank; NKP, Northern Kerguelen Plateau; CKP, Central Kerguelen Plateau; SKP, Southern Kerguelen Plateau. The Elan Bank area is outlined in orange. Blue areas off the Antarctic coast indicate permanent ice. (Original in colour) (after Borisshova *et al.*[8]).

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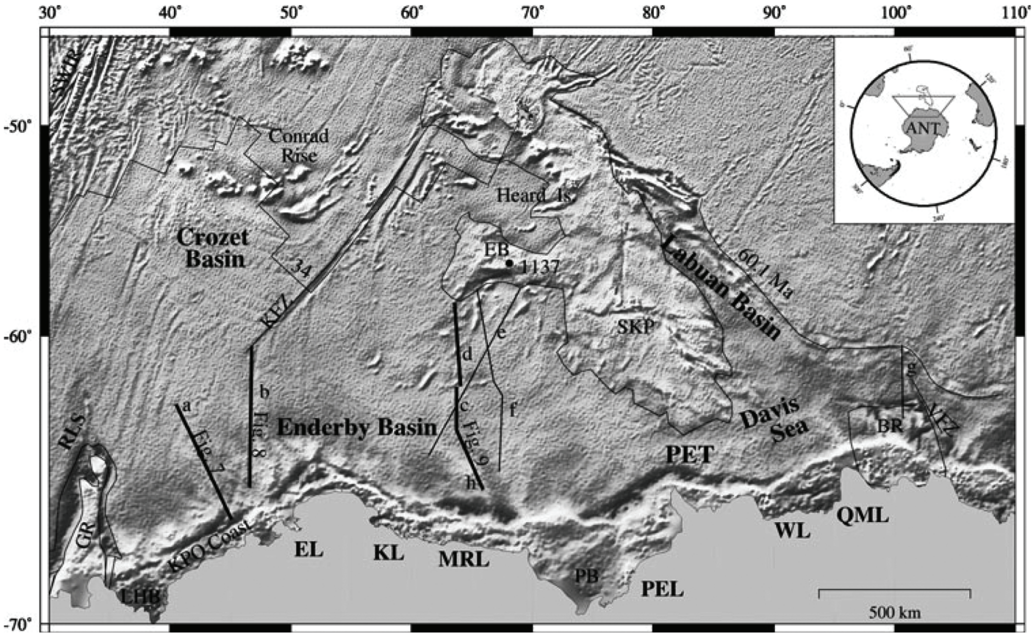

Figure 2. Satellite-derived marine free-air gravity field along the East Antarctic margin, between Gunnerus Ridge and Bruce Rise (outlined), illuminated with an azimuth of 330°S (ref. 7). Lineament labelled 60.1 Ma indicates approximate timing and zone of break-up between Broken Ridge and Kerguelen Plateau (outlined). 1137, ODP Leg 183-Site 1137; BR, Bruce Rise; EB, Elan Bank; EL, Enderby Land; GR, Gunnerus Ridge; KFZ, Kerguelen Fracture Zone; KL, Kemp Land; KPO Coast, Kron Prinz Olav Kyst; MRL, Mac. Robertson Land; PB, Prydz Bay; PEL, Princess Elizabeth Land; PET, Princess Elizabeth Trough; LHB, Lutzow–Holm Bay; QML, Queen Mary Land; RLS, Riiser–Larsen Land; SKP, Southwest Indian Ridge; VFZ, Vincennes Fracture Zone; WL, Willem II Land (after Gaina *et al.*[7]).

Bay of Bengal (BoB), formed during 80–130 Ma, evolved in two stages – the initial rifting and drifting of the Indian subcontinent from East Antarctica (~130 Ma), followed by seafloor spreading and subsequent breakup of the Elan Bank from the Indian continental margin[7]. Majumdar and Bhattacharyya[5] have successfully delineated the continental margins in the Indian offshore using high-resolution satellite geoid/gravity data. Figure 1 shows the location of the Elan Bank, Antarctica. Figure 2 shows a three-dimensional perspective view of the free-air gravity anomaly over a part of BoB[7–9]. The transition between the continental and oceanic crust was originally created by rifting, and is known as a passive margin. In turn, the active margins were formed by the break-up of India from East Antarctica in the Early Cretaceous period. Detachment of micro-continents and excessive sediment deposition on continental margins add more complexities to the ocean floor as well to continental regions, making it difficult to reconstruct precise plate tectonic history. These processes may lead to the trapping of micro-continental pieces within the oceans and oceanic territories beneath land masses. Accordingly, one can rarely find ancient, continental, sliver-like Seychelles micro-continents in the north-western Indian Ocean[9,10] and Elan Bank in the southern Indian Ocean[7–10] encircled by oceanic crustal rocks; it is even more rare to find oceanic rocks beneath land-masses. Predicted bathymetry[11] of the Elan Bank showing the distribution of seaward-dipping reflection complexes, major faults and the possible southern limit of the continent–ocean transitional zone, mapped from the seismic data[8]. Global gravity models can identify geoidal undulations, but are restricted by spatial declarations. Local area geoid heights are determined by Global Positioning System (GPS)-levelling observations or calculated from terrestrial gravity values. Map coordinates of the study area are 54–60°S, 60–75°E. Predicted bathymetry over the Elan Bank and its surroundings varies between 1000 and 2000 m. Predicted bathymetry from satellite-derived geoid/gravity over a part of the BoB has been discussed elsewhere[12].

The major objectives of this study are: (i) to generate the residual geoid anomaly over the Elan Bank, and (ii) to assess the characteristics of the Elan Bank plate. There is a lot of ambiguity on the timing of continental break-up from the eastern Gondwanaland[13]. It is, as such, well-known that when continental and oceanic plates collide, the thinner and more dense oceanic plate is overridden by the thicker and less dense continental plate, which is thus forced down into the mantle in a process known as subduction.

Geoid is defined as the equipotential surface coinciding with the mean sea level in the oceans, provided the latter is affected by no force other than the earth's gravity field. The sea surface altimeter is a nadir-viewing instrument which transmits short-duration pulses (frequency ~13.0 GHz) with known power in a pencil beam towards the earth's surface and then measures the reflected energy, thereby calculating the sea surface height (SSH)[14]. Hence, repeated altimeter observations taken at the same location over a period of time are used to deduce the marine geoid, which is related to the shape of the earth. Marine geoid is an equipotential surface reflecting mass distribution inside the earth[15]. As the geoid by definition refers to this theoretical surface, the mean of the repeated altimetric SSH provides a reasonable estimation and is referred to as the classical geoid in the terminology of this study. The geoid contains information regarding mass distribution inside the entire earth, including variations in sea bottom topography. The classical geoid is also used to compute residual and prospecting geoids – hypothetical surfaces related to the mass distribution in various lithospheric zones[14–18]. However, the primer method for geoid determination nowadays is satellite gravimetry. For dedicated satellite missions, e.g. CHAMP, GRACE or GOCE[18,19], satellite altimetry can provide an alternative tool for determining the geoid over the oceanic regions[18,20]. Measurements of sea surface have shown that it is not flat all over the globe, since undulations of a few centimetres to several hundred metres have been measured. These sea surface undulations have time-dependent components because of the influence of winds, currents, tides, etc. and time-independent components (permanent undulations) created by density variation on and below the seafloor. These time-independent undulations are used in the prediction of satellite geoid/gravity to map the density contrasts inside the earth.

Gravity/magnetic-related studies have been conducted by Gaina *et al.*[7] and Borisshova *et al.*[8], and signature matching over the ocean-related areas could be observed with geoidal studies. However, the same is not true for geoid-related studies over the Elan Bank, which is considered as a continental lithosphere[8,21]. Krishna *et al.*[13] analysed geoid and gravity anomaly data of conjugate regions of BoB and the Enderby Basin, Antarctica, with new constraints on break-up and spreading history between India and Antarctica. Krishna *et al.*[21] have also studied the ocean floor hidden beneath Bangladesh.

A fundamental geophysical parameter used for various oceanographic and geophysical studies is the satellite geoid, which can be obtained from instantaneous SSH[22–25]. So SSH as measured by satellite altimeter is averaged from time to time to obtain the satellite geoid

$$\text{SSH} = \text{Orbit height } (H) - \text{corrected altimetric range } (h'). \quad (1)$$

The residual geoid undulations were extracted from the observed geoid undulations after removing the deeper earth effects[23,24]. A fast Fourier transform (FFT) approach uses geoid data to compute the free-air gravity anomaly based on flat earth approximation and is derived from the two fundamental equations, namely Brun's equation and the equation of physical geodesy[24]. The relation between gravity anomaly and the geoid undulation derived is given by Chapman[25]

$$F(\Delta g) = g_0\,|k| F(N), \quad (2)$$

where $F(\Delta g)$ is the Fourier transform of free-air gravity anomaly, $F(N)$ the Fourier transform of the geoid undulation and $|k|$ is the one-dimensional wavenumber associated with wavelength λ.

Details of generation of satellite geoid, residual geoid and prospecting geoids are discussed elsewhere[16,17].

As indicated earlier, three characteristic contributions could be found in the geoid estimation, namely bathymetric contribution, lithospheric contribution as measured and contribution due to the deeper earth[24]. The contribution due to the deeper earth is removed using spherical harmonic coefficients (Rapp's coefficients) expanded up to degree and order 50, to obtain the residual geoid[4]. Bathymetry data along the satellite track obtained from ETOPO2 and naval hydrographic charts were used to model the geoidal contribution due to bathymetry.

The residual geoid map and the related bathymetry information could be generated over the Elan Bank. Geoid and bathymetry data together provide constraints on the earth's elastic response and thus on the cooling process of the oceanic lithosphere. The gravity maps prepared from satellite altimeter data are a perfect reconnaissance tool for planning more detailed ship-borne surveys.

Structural features like Northern Kerguelen Plateau (NKP) (Kerguelen Island), Central Kerguelen Plateau (CKP) (Heard and Mcdonald Islands) and the South Kerguelen Plateau (SKP) could be identified in the geoidal map (Figures 1–3). However, Elan Bank, where the land basement exists, shows a faint signature in the satellite geoid-related studies (Figure 3). In general, the continental crust is less-dense and thicker in size. Accordingly, its signature is not quickly visible in the geoidal map. The Elan Bank could be sharply detected in magnetic images (Figure 1)[8]. However, it is not clear in the gravity image (Figure 2). Compared to the sediment loading on the top of the Elan Bank, processed and filtered gravity data/images have shown tectonics sharply. This has been reflected in its textured data/image of the subsurface tectonics.

Predicted bathymetry over the Elan Bank and its surroundings varied between 1000 and 2000 m. Continental sliver could also be seen on the right-hand side of NKP (Figures 1 and 3). Large, primitive oceanic rocks of BoB were buried under large volumes of terrigenous sediments as carried out by the Ganges and the Brahmaputra from the Himalaya, which totally buried a major part of Bangladesh that was an earlier neighbour of the Elan Bank. The presence of continental slivers in global oceans, either

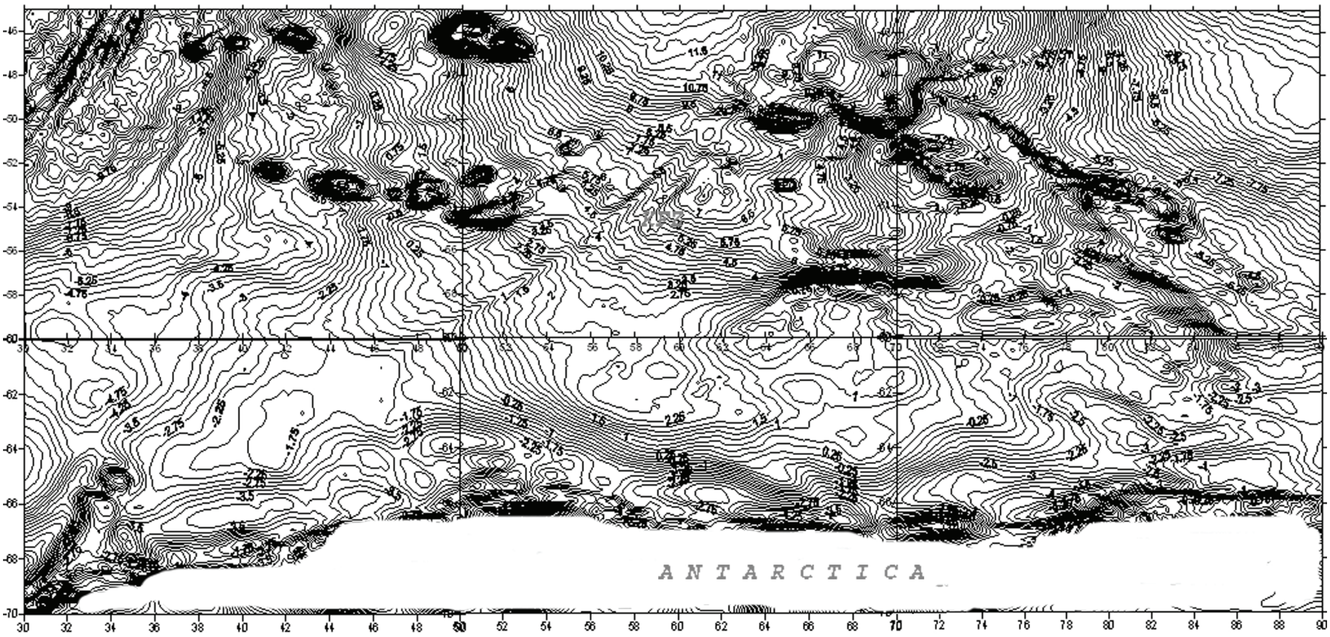

Figure 3. Generated high-resolution residual geoid image over the Elan Bank and its surroundings.

completely buried under the sediments or surviving as islands, is known[21].

In general, satellite geoid/gravity mapping of the Elan Bank and other features in ECMI could be done successfully. However, geoid mapping is a comparatively new field, which needs further studies. Also, it can be used as a perfect reconnaissance tool and as another source of data along with seismic, magnetic, etc. Accumulation of six frames for more significant data generation and further analysis will be beneficial for higher resolution geoidal mapping (Figure 3). Continental slivers tracking in the Antarctic region is a novel effort with geoidal maps. These studies further confirm the continental nature of the lithospheric plate below the Elan Bank, Antarctica. Similar studies could be performed over the Seychelles continental margin in future with satellite geoid data.

1. Brennecke, J. and Lelgemann, D., The altimetric geoid in the North Sea. In *Satellite Microwave Remote Sensing* (ed. Allan, T. D.), John Wiley, 1983, p. 526.
2. Haxby, F., Karner, G. D., La Brecque, J. L. and Weissel, J. K., Digital images of combined oceanic and continental data sets and their uses in tectonic studies. *EOS Trans.*, *Am. Geophys. Union*, 1983, **64**, 995–1004.
3. Sandwell, D. T. and McAdoo, D. C., Marine gravity of southern Indian Ocean and Antarctic margins from Geosat. *J. Geophys. Res*., 1988, **93**, 10389–10396.
4. Rapp, R., The determination of geoid undulations and gravity anomalies from Seasat altimeter data. *J. Geophys. Res*., 1983, **88**, 1552–1562.
5. Majumdar, T. J. and Bhattacharyya, R., Delineation of continental margin in the Indian offshore using high resolution satellite geoid/gravity data. *Space Res. Today*, 2013, **188**, 8–14.
6. Bhattacharya, G. C. and Chaubey, A. K., Western Indian Ocean – a glimpse of the tectonic scenario. In *The Indian Ocean – A Perspective* (eds Sen Gupta, R. and Desa, E.), Oxford & IBH Publishers, New Delhi, 2001, pp. 691–729.
7. Gaina, C. *et al*., Breakup and early seafloor spreading between India and Antarctica. *Geophys. J. Int*., 2007, **170**, 151–169.
8. Borisshova, I. *et al*., Structure and development of a micro continent: Elan Bank in the southern Indian Ocean. *Geochem. Geophys. Geosyst. J*., 2003, **4**, 16; doi:10.1029/2003GC000535.
9. Shor, G. G. and Pollard, D. D., Origin and development from Pangaea to Gondwanaland to recent times. *Science*, 1963, **142**, 48–49.
10. Davies, D. and Francis, T. J. G., The crustal structures of Seychelles Bank. *Deep-Sea Res*., 1964, **11**, 921–927.
11. Smith, W. H. F. and Sandwell, D. T., Global sea floor topography from satellite altimetry and ship depth soundings. *Science*, 1997, **277**, 1956–1962.
12. Bhattacharyya, R. and Majumdar, T. J., Bathymetry prediction over a part of the Bombay High in the western offshore using very high resolution satellite gravity data. *Curr. Sci*., 2009, **97**, 1152–1161.
13. Krishna, K. S., Laju, M., Bhattacharyya, R. and Majumdar, T. J., Geoid and gravity anomaly data of conjugate regions of Bay of Bengal and Enderby Basin: new constraints on breakup and spreading history between India and Antarctica. *J. Geophys. Res*., 2009, **114**, B03102; doi:10.1029/2008JB005808.
14. Fu, L. L., Chelton, D. B. and Zlotnicki, V., Satellite altimetry: observing ocean variability from space. *Oceanography*, 1988, **1**, 4–11.
15. Lundgren, B. and Nordin, P., Satellite altimetry: a new prospecting tool. In Proceedings of the Sixth Thematic Conference, Colorado, Environmental Research Institute of Michigan, Ann Arbor, USA, 1988, pp. 565–575.
16. Majumdar, T. J. and Bhattacharyya, R., An atlas of very high resolution satellite geoid/gravity over the Indian offshore. SAC Technical Note No. SAC/RESIPA/MWRG/ESHD/TR-21/2004, p. 48.
17. Rajesh, S. and Majumdar, T. J., Generation of 3-D geoidal surface of the Bay of Bengal lithosphere and its tectonic implications. *Int. J. Remote Sensing*, 2004, **25**, 2897–2902.
18. Foldvary, L. and Fukuda, Y., IB and NIB hypotheses and their possible discrimination by GRACE. *Geophys. Res. Lett*., 2001, **28**(4), 663–666; https://doi.org/10.1029/2000GL011775.

19. Sneeuw, N. *et al.*, One year of time-variable CHAMP-only gravity field models using kinematic orbits. In *A Window on the Future of Geodesy*, IAG Symposium Series, Springer Verlag, 2004, vol. 128, pp. 288–293; doi:10.1007/3-540-27432-4_49.
20. Chander, S. and Majumdar, T. J., Comparison of SARAL and Jason-1/2 altimetry-derived geoids for geophysical exploration over the Indian offshore. *Geocarto Int.*, 2015, **31**(2), 18; http://dx.doi.org/10.1080/10106049.2015.1041562.
21. Krishna, K. S. *et al.*, Ancient ocean floor hidden beneath Bangladesh. *Curr. Sci.*, 2019, **117**(6), 916–917.
22. Wakker, K. F., Zandbergen, R. C. A., van Geldorp, G. H. M. and Ambrosius, B. A. C., From satellite altimetry to ocean topography: a survey of data processing techniques. *Int. J. Remote Sensing*, 1988, **9**, 1797–1818.
23. Hwang, C., Hsu, H.-Y. and Jang, R. J., Global mean surface and marine gravity anomaly from multi-satellite altimetry: application of deflection-geoid and inverse Vening Meinesz formulae. *J. Geod.*, 2002, **76**, 407–418.
24. Majumdar, T. J., Mohanty, K. K. and Srivastava, A. K., On the utilization of ERS-1 altimeter data for offshore oil exploration. *Int. J. Remote Sensing*, 1998, **9**, 1953–1968.
25. Chapman, M. E., Techniques for interpretation of geoid anomalies. *J. Geophys. Res.*, 1979, **84**, 3793–3801.

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Ecological footprint of Solan district, Himachal Pradesh, India

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Unsustainable resource use on earth must be addressed from a variety of perspectives and at multiple levels of governance. Understanding the environmental consequences of urban-dwellers will become increasingly important as the human population urbanizes. Having access to reliable, cross-cutting, quantitative city-level sustainability measures is crucial. By taking into account local facts, scientific analyses can assist in providing solutions. Emergence analysis, material flow analysis, data development analysis and ecological footprint analysis (EFA) are only some of the assessment methodologies that have been offered. EFA has been used to assess urban sustainability in a number of cities as a useful analytical and planning tool. The purpose of this study is to assess the sustainability of Solan district, Himachal Pradesh, India, using four EFA components: crop land, grazing land, forest land and infrastructure land footprints. According to the study, the total ecological footprint of Solan district is 6865.30 gha, and its components are in the following order: crop land footprint (3287.40 gha) > infrastructure land footprint (2088.21 gha) > grazing land footprint (978.03 gha) > forest land footprint (511.67 gha).

Keywords: Crop land, ecological footprint analysis, forest land, grazing land, infrastructure land, sustainability.

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REES[1] introduced the ecological footprint (EF), which has been widely used as a comprehensive assessment of anthropogenic impact on the environment[2,3]. The examination of EF for smaller systems, such as provinces or cities, or even a single household or business structure, allows for the assessment of system sustainability and future development strategies[4]. Sustainable development management is ultimately concerned with earth's ability to support human societies[5]. Living within the means of the sole planet available to humanity is the first step toward building a future society in which everyone may thrive[6]. However, 'one planet' is a backdrop that forms our reality[7], not a goal. Sustainability is described as the process of achieving demonstrable long-term societal development through environmental, economic and social actions. Sustainability is a multidisciplinary issue, with no single statistic capable of addressing its entire complexity[8]. To address this, decision-makers must sift through a plethora of data, information and indicators[9]. In order to attain sustainability, the use of sustainability indicators is becoming increasingly important[10]. Sustainability indicators provide a solid foundation for regular and long-term monitoring of progress toward strategic development goals, as well as assessment of various types of sustainability[11]. Economic, social and environmental indicators are the three types of sustainability indicators. EF is sustainability indicator with an environmental focus. The aim of the present study is to determine the EF of Solan district, Himachal Pradesh (HP), India. EF is a measure of the environmental implications of modernization that outstrip those of the surrounding areas. Ecological footprint analysis (EFA) is defined as a synthetic method for tracking human impacts on an environmental system's regenerative capacity by identifying the amount of bioproductive land required to support average annual consumption and waste production of a given entity under current technologies[12]. Cropland, carbon land, grazing land, fishing grounds, forest land and infrastructure land are the six components of EF accounting. The sum of these elements yields an estimate of EF[4]. Cropland, grazing land, forest