to detecting two spatially separated clusters of *P. juliflora*, the L-band cross-polarized SAR was found to be best suited as two distinct peaks were observed for it. Whereas the C-band cross-polarized SAR could not give two distinct peaks corresponding to two tree clusters. Instead the two clusters appeared as more or less as a single cluster on the C-band cross-polarized SAR image. The X band could not detect the presence of thin vegetation volume for any of the three cases taken up in this study, as the thin vegetation failed to have any impact on the X band SAR in comparison to its surrounding features. Thus the overall L-band cross-polarized SAR was found to be the most suitable for detecting thin vegetation volume in the present study.

1. Hsu, C. C., Wang, L., Kong, J. A., Souyris, J. C. and Le Toan, T., Theoretical modeling for microwave remote sensing of forest. In International Symposium on the Retrieval of Bio- and Geophysical Parameters from SAR Data for Land Applications, Toulouse, France, 1995.
2. Kasischke, E. S. and Christensen, N. L., Connecting forest ecosystem and microwave backscatter models. *Int. J. Remote Sensing*, 1990, **11**, 1277–1298.
3. Souyris, J. C., Le Toan, T., Hsu, C. C. and Kong, J. A., Inversion of land forest biomass using SIR-C/X-SAR data: Experiment and theory. In International Symposium on the Retrieval of Bio- and Geophysical Parameters from SAR Data for Land Applications, Toulouse, France, 1995.
4. Srivastava, H. S., Patel, P., Sharma, Y. and Navalgund, R. R., Detection and density mapping of forested areas using SAR interferometry technique. *Inter. J. Geoinf.*, 2007, **3**, 1–10.
5. Ulaby, F. T. and Dobson, M. C., *Handbook of Radar Scattering Statistics for Terrain*, Artech House, Norwood, MA, 1989.
6. Henderson, F. M. and Lewis, J., *Principles and Applications of Imaging Radar: Manual of Remote Sensing*, John Wiley & Sons, Inc., NY, 1998, vol. 2, 3rd edn, pp. 461–465.
7. Dobson, M. C., Ulaby, F. T., LeToan, T., Beaudoin, A., Kasischke, E. S. and Christensen, N., Dependence of radar backscatter on coniferous forest biomass. *IEEE Trans. Geosci. Remote Sensing*, 1992, **30**, 412–415.
8. Dobson, M. C. *et al.*, Estimation of forest biophysical characteristics in northern Michigan with SIR-C/X-SAR. *IEEE Trans. Geosci. Remote Sensing*, 1995, **33**, 877–895.
9. Ulaby, F. T., Moore, R. K. and Fung, A. K., *Microwave Remote Sensing: Active and Passive*, Artech House, Norwood, 1990, vols II & III.
10. Patel, P., Srivastava, H. S., Panigrahy, S. and Parihar, J. S., Comparative evaluation of the sensitivity of multi-polarized multi-frequency SAR backscatter to plant density. *Int. J. Remote Sensing*, 1996, **27**, 293–305.
11. http://southport.jpl.nasa.gov/sir-c/html/mission.html
12. Kierein-Young, K. S., Lefkoff, A. B. and Kruse, F. A., Radar Analysis and Visualization Environment (RAVEN): Software for Polarimetric Radar Analysis. In Third Annual JPL Airborne Geoscience Workshop (AIRSAR Workshop), JPL Publication, 1992, vol. 3, pp. 78–80.
13. Lee, J. S., Speckle suppression and analysis for SAR images. *Opt. Eng.*, 1986, **25**, 636–643.

ACKNOWLEDGEMENTS. We thank Dr V. Jayaraman, Director, National Remote Sensing Centre, Hyderabad for keen interest in this study. H.S.S. and P.P. thank Dr Y. V. N. Krishnamurthy, Director, Regional Remote Sensing Service Centre/National Natural Resources Management System (RRSSC/NNMRS), ISRO Head Quarters, Bangalore; Dr J. S. Parihar, Deputy Director, Remote Sensing Applications Area, Space Applications Centre, Ahmedabad; Dr K. P. Sharma, Head-In-charge, RRSSC-Dehradun; Dr M. Chakraborty, Group Director, Geo-Informatics and Techniques Development Group and Dr S. Mohan, Head, Advance Techniques Development Division for support and encouragement.

Received 4 September 2008; revised accepted 10 June 2009

The Great avulsion of Kosi on 18 August 2008

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The 18 August 2008 avulsion of the Kosi River draining the parts of north Bihar in eastern India may well be regarded as one of the greatest avulsions in a large river in recent years. The Kosi River shifted by ~120 km eastward, triggered by the breach of the eastern afflux bund at Kusaha in Nepal at a location 12 km upstream of the Kosi barrage. This event was widely perceived as a major flood in the media and scientific circles. Although a large area was indeed inundated after this event, it is important to appreciate that this inundation was different from a regular flooding event.

Keywords: Floods, Ganga plains, Kosi barrage, river dynamics, river management.

RIVERS play a critical role in human society and history as they are the major source of fresh water, transportation, and resources. However, this relationship is often ‘troubled’ because changes in river discharge (floods or droughts) or position can play havoc with permanent settlements. Such changes can be caused by natural forcing as well as human interventions, or a combination of both. Natural processes may include short-term changes in sediment load or water volume as well as long-term changes in relative sea level or climate change. The human interventions impact changes in sediment load or run-off through water resource management schemes such as dams, barrages and embankments. Human alterations of river systems can have many important consequences, primarily because river systems are dynamic and highly integrated systems and, any change in any part of the river can easily propagate and affect the whole system.

The Kosi River is an important tributary of the Ganga in the eastern India (Figure 1 *a*) and has distinctive hydro-

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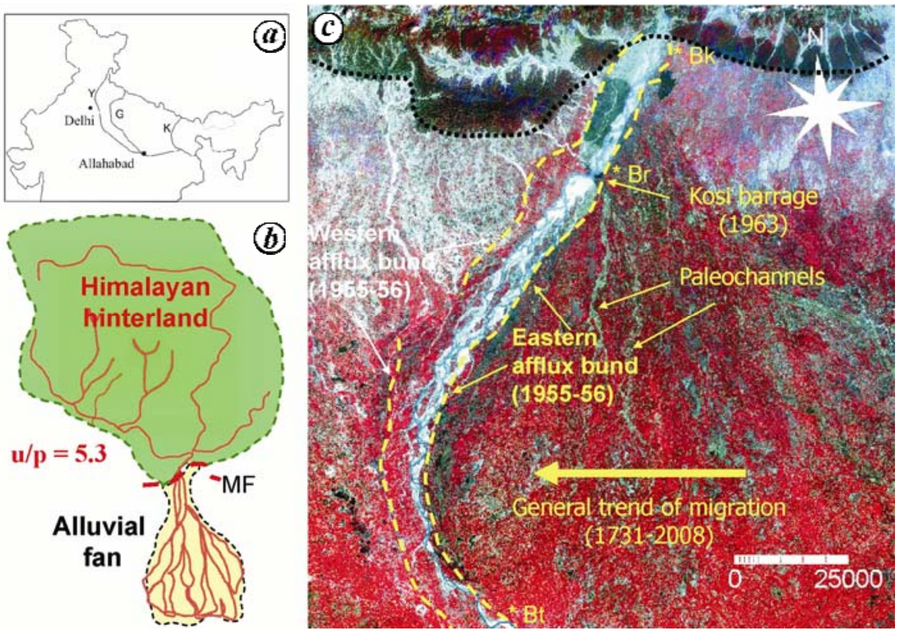

Figure 1. ***a***, Location map showing the position of the Kosi River in eastern Ganga plains (G, Ganga; Y, Yamuna; K, Kosi). ***b***, The Kosi River has a large mountainous catchment in Nepal and a rather small alluvial area in north Bihar giving rise to a large upland/alluvial (u/p) ratio; ***c***, The historical records suggest a dominant westward migration of the Kosi River during the last ~200 years before the river was embanked on both sides by 1956.

Table 1. Major hydrological and sediment transport characteristics of the Kosi River. Note that the Kosi has a high sediment yield which has to be accommodated in a rather small alluvial area (u/p ratio is 5.3, see Figure 1 *b*)

Parameter	Kosi	Ganga	Amazon
Catchment area (10^3 km^2)	101	1073	7180
Total length (km)	1216	2700	6518
Average annual discharge (m^3/s)	2036	15,000	480,000
Annual sediment load at river mouth (mt/yr)	43	1670	1000
Discharge/area	20	14	25
Sediment yield (mt/y/km^2)	0.43	1.56	0.14

logical and sediment transport characteristics (Table 1). The dynamics of the Kosi River, generally described as ‘avulsive’ shifts, has been well documented by previous workers[1–3] and a preferentially westward movement of 150 km in the last 200 years has been recorded (Figure 1 *c*). Various explanations for this unidirectional shift of the Kosi include sedimentation in a braided stream[4], cone building activity[2], active tectonics[5,6], and autocyclic and stochastic movements[3]. Avulsion involves a sudden movement around a nodal point (divergence point) and occurs when an event of sufficient magnitude (usually a flood) occurs along a river that is at or near avulsion threshold[7] defined by the changing channel instability through time. It also implies that avulsion may not always be triggered by the largest flood in a given river, and that even a small flood can trigger an avulsion if the river is close to avulsion threshold. One of the most common mechanisms of avulsion is ‘channel reoccupation’ (rapid) when the new channel occupies a pre-existing channel in the vicinity. On the other hand, ‘crevasse splaying’ involves a gradual process of breaching through the banks and development of a new channel through time. Not just Kosi, several rivers draining the plains of north Bihar are known for frequent and rapid avulsions[8–10] and the area is prone to fluvial hazards[11,12].

Unlike the previous westward avulsions (Figure 1 *c*), the 18 August 2008 avulsion of the Kosi River recorded an eastward jump of ~120 km which is an order of magnitude higher than any single avulsive shift recorded in historical times. The avulsion was triggered by a breach in the eastern afflux bund of the Kosi at Kusaha, 12 km upstream of the Kosi barrage (Figure 2 *a* and *b*). This avulsed channel ‘reoccupied’ one of the palaeochannels of the Kosi and 80–85% flow of the river was diverted into the new course. Since the new course had a much lower carrying capacity, the water flowed like a sheet, 15–20 km wide and 150 km long with a velocity of 1 m/s at the time of breach. Interestingly, the new course did not join back the Kosi nor did this find through-drainage into the Ganga, as a result of which a very large area remained inundated/waterlogged for more than four months after the breach. This single event affected more than 30 million people and there is still no reliable estimate of loss of life and property.

Several lines of evidence coupled with ground observations support that this event was a ‘mega-avulsion’ rather than a regular flood.

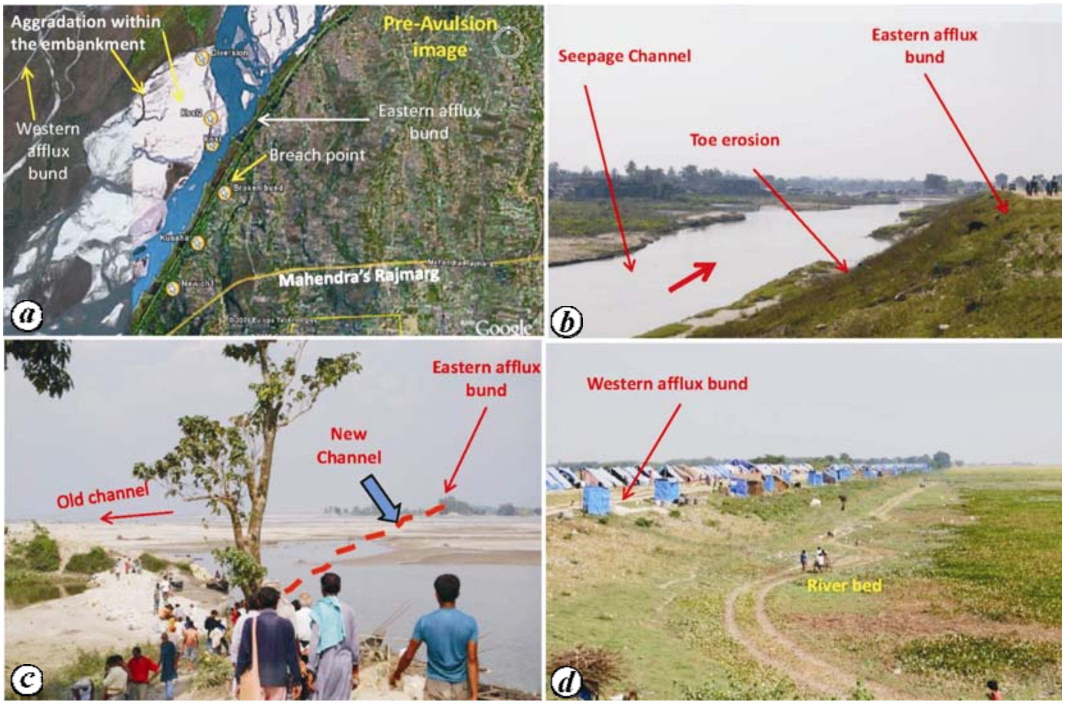

Figure 2. ***a***, Google image showing the course of the Kosi River before avulsion and the breach point at Kusaha; ***b***, Part of the eastern afflux washed away after the breach and the river avulsed towards the east; ***c***, Seepage channel outside the eastern afflux bund causing significant toe erosion; ***d***, The western side of river bed and the afflux bund – river bed is 4–5 m higher than the adjoining flood plain.

Simulations for understanding the avulsion mechanism suggest that avulsion points shift up-valley followed by an abrupt down-valley shift as a result of continued growth of alluvial ridges and increase in cross-valley slope upstream of avulsion locations[13]. Specific simulations for the Kosi also predicted the pseudo-nodal style of the progressive westward shift and it was also suggested that channel belt would start shifting towards the east once the avulsing channel belts encounter a barrier created by the depositional topography of the fan[13]. Although the observational data from the Kosi[2,3] show a down-valley shift in avulsion sites through time, the river has a tendency to periodically return to the upstream nodal point.

It has also been suggested that a decrease in inter-avulsion period occurs through time[7,13,14] because the probability of avulsion increases due to decrease in overall channel belt slope. Data from Kosi shows a decrease in inter-avulsion period[7,14] between 1700 and 1955. A sharp increase in the inter-avulsion period around 1955 coincides with the construction of embankments along both banks of the Kosi which should have stabilized the channel temporarily.

The breach at Kusaha occurred at a discharge of 144,000 cusecs which is much less than the design discharge of 950,000 cusecs for the barrage upstream and the afflux bunds. The river avulsed following the breach, occupied one of its palaeochannels and inundated large areas as the channel capacity of the new course was very small.

Repeated satellite images show that the Kosi River around Kusaha was flowing very close to the eastern afflux bund at least since 1999 and there are reports that a couple of spurs upstream of the breach point were eroded in the last few years. During the field visit, it was also observed that a well-defined seepage channel (Figure 2 *c*) outside and parallel to the eastern afflux bund formed some years ago. This channel has also been causing significant toe erosion of the afflux bund. Further, the afflux bunds are more than 50 years old and have been poorly maintained which may have facilitated the breach and the avulsion.

In contrast, the channel has been aggrading on the western side with an accelerated rate after the construction of embankment. This is not surprising as the Kosi is among the highest sediment-laden river in the world[15] (0.43 mt/y/km^2; see Table 1). The river bed around the western afflux bund was observed to be at least 4–5 m higher than the surrounding floodplain level (Figure 2 *d*) although no measurement of the rate of channel bed aggradation is available at this stage. This suggests that most of the sediment load was trapped within the embankment and the river developed a 'gradient advantage' as the cross valley slope exceeded the down-valley slope in this region (Figure 3). This made the eastern afflux bund vulnerable to breach and pushed the river close to 'avulsion threshold'.

This avulsion triggered by the breach, has once again questioned the efficacy of the embankment strategy for flood control. Even a casual look at the data and interactions with local people in the Kosi region would reveal that there has been no appreciable flood moderation in the Kosi and other rivers of north Bihar even after the construction of embankments and the barrage (designed with a flood cushion). The embankment strategy for flood control as well as several other human interventions such as highways and railway embankments have also produced severe drainage congestion in the region which results in longer inundation of large areas almost every year. There is an urgent need to adopt an 'integrated' river basin management which requires a rigorous understanding of the physical processes by which river channels are formed and maintained, and encompasses all physical attributes of the earth's surface involved in water cycle.

The 18 August avulsion of the Kosi triggered by the breach at Kusaha occurred partly due to incorrect strategies of river management and partly due to human negligence and poor maintenance of the afflux bund for the last several years. This means that this avulsion was partly a 'human disaster' rather than regular flooding.

The Kosi River was diverted back into the old course through the barrage on 26 January 2009 after restoring about 2000 m long embankment which was breached on 18 August 2008. The big question now is: how long the river will stay in this course and when will the next breach/avulsion occur? The conditions which led to the breach and avulsion of the river, i.e. aggraded river bed within the poorly maintained embankment, remain as they were before the avulsion. The sustenance of the plugging of breach is questionable and the possibility of another breach in the near future at other locations cannot be ruled out. A good possibility should have been to use the new course as a diversion channel for the excess water during floods and to follow the age-old practice of 'controlled' flooding. Perhaps a few other palaeochannels of the Kosi can be surveyed and a system of channel network can be developed as a long-term effort. The course of the river through the barrage and within the embankment would need significant channel improvement perhaps through dredging in selected reaches. Till today, no attempts have been made to improve the channel or strengthen the embankment.

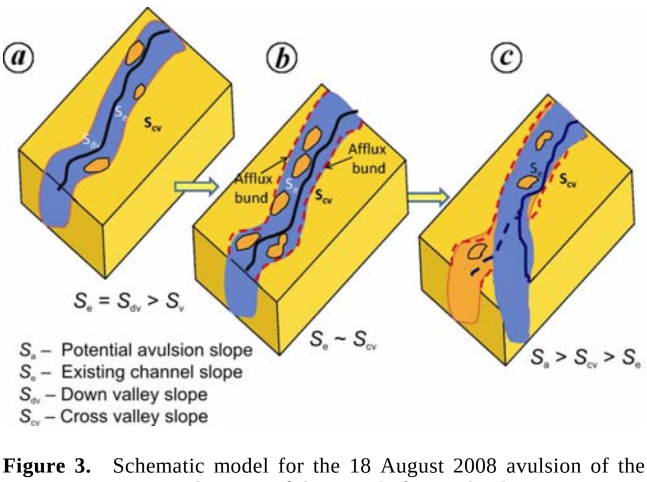

Figure 3. Schematic model for the 18 August 2008 avulsion of the Kosi River. ***a***, Natural course of the river before embankment construction; large floods passed through the channel and avulsion threshold was higher. ***b***, River embanked on both sides resulting in accelerated aggradation; frequent breaches through small floods, reduction in stream power and lowering of avulsion threshold. ***c***, Crossing of avulsion threshold triggered by 'gradient advantage' (increase in Sa/Se) caused by aggradation.

While a great deal of research needs to be done to find a long-term solution to the Kosi avulsion and flooding, it is important that a 'system' approach to river management should be adopted keeping in view the dynamic behaviour of the Kosi. Further, there has been a paradigm shift globally from 'river control' primarily involving an engineering approach addressing the 'effect' at a local scale to 'river management' which emphasizes an integrated approach at a crossover of scales and addresses the 'cause' rather than the effect[16–19]. Even though India is a country bestowed with several large rivers, our river management strategies are rather rudimentary and our planners are yet to embrace modern approaches such as satellite-based monitoring and multi-criteria decision support system. Some efforts in this direction[20,21] have already shown encouraging results but a large-scale, coordinated effort is needed to save a large population from repeated miseries of fluvial hazards year after year. A process-based understanding of the Kosi and the coupling between river form and processes are needed to find long-term solutions to river dynamics and floods.

1. Shillingfield, 1893; cited in Gole and Chitale, 1966 (see ref. 2).
2. Gole, C. V. and Chitale, S. V., Inland delta building activity of Kosi River. *J. Hydraul. Div., ASCE*, 1966, **92**, 111–126.
3. Wells, N. A. and Dorr, J. A., Shifting of the Kosi River, northern India. *Geology*, 1987, **15**, 204–207.
4. Leopold, L. B. and Maddock, T., Flood control problems. *J. Soil. Water Conserv. India*, 1955, **3**, 169–173.
5. Arogyaswamy, R. N. P., Some geological factors influencing the behaviour of the Kosi. *Rec. Geol. Surv. India*, 1971, **96**, 42–52.
6. Agarwal, R. P. and Bhoj, R., Evolution of Kosi river fan, India: structural implication and geomorphic significance. *Int. J. Remote Sensing*, 1992, **13**, 1891–1901.
7. Jones and Schumm, S. A., Causes of avulsion: an overview. In *Fluvial Sedimentology VI* (eds Smith, N. D. and Rogers), Spl. Pub. Int. Ass. Sedimentol., 1999, vol. 28, pp. 171–178.
8. Sinha, R., Channel avulsion and floodplain structure in the Gandak–Kosi interfan, north Bihar plains, India. *Z. Geomorph.*, Suppl.-Bd, 1996, **03**, 249–268.
9. Jain, V. and Sinha, R., Fluvial dynamics of an anabranching river system in Himalayan foreland basin, Baghmati River, north Bihar plains, India. *Geomorphology*, 2004, **60**, 147–170.
10. Jain, V. and Sinha, R., Hyperavulsive-anabranching Baghmati river system, north Bihar Plains, eastern India. *Z. Geomorph.*, 2003, **47**, 101–116.
11. Sinha, R. and Jain, V., Flood hazards of North Bihar Rivers, Indo-Gangetic Plains. *Mem. Geol. Soc. India*, 1998, **41**, 27–52.
12. Sinha, R., On the controls of fluvial hazards in the north Bihar plains, eastern India. Engineering Geology Spl. Publication 15, Geological Society of London, 1998, pp. 35–40.

13. Mackey, S. D. and Bridge, J. S., Three dimensional model of alluvial stratigraphy: theory and application. *J. Sed. Res.*, 1995, **365**, 7–31.
14. Stouthamer, E. and Berendsen, H. J. A., Avulsion: the relative roles of autogenic and allogenic processes. *Sed. Geol.*, 2007, **198**, 309–325.
15. Sinha, R. and Friend, P. F., River systems and their sediment flux, Indo-Gangetic plains, northern Bihar, India. *Sedimentology*, 1994, **41**, 825–845.
16. Gilvear, D. J., Fluvial geomorphology and river engineering: future role utilizing a fluvial hydrosystems framewok. *Geomorphology*, 1999, **31**, 229–245.
17. Downs, P. W. and Gregory, K. J., *River Channel Management*, Arnold Press, 2004, p. 395.
18. Brierley, G. J. and Fryirs, K., *Geomorphology and River Management: Applications of the River Styles Framework*, Blackwell Publishing, Oxford, 2005, p. 398.
19. Brierley, G. J. and Fryirs, K., *River Futures. An Integrative Scientific Approach to River Repair*, Island Press, Washington, 2005, p. 304.
20. Bapalu, G. V. and Sinha, R., In *Flood Hazard Mapping: A Case Study of Kosi River Basin*, GIS@Development online edition, October 2005.
21. Sinha, R., Bapalu, G. V., Singh, L. K. and Rath, B., Flood risk analysis in the Kosi river basin, north Bihar using multi-parametric approach of Analytical Hierarchy Process (AHP). *J. Indian Soc. Remote Sens.*, 2008, **36**, 293–307.

ACKNOWLEDGEMENTS. I thank Barh Jan Ayog Bihar for organizing a visit to the flood affected areas in Nepal and north Bihar including the breach point at Kusaha. Discussions with several persons namely, Dr Manas Bihari Verma, Dr Ajaya Dixit, Dr Deepak Gywali, Mr Vijay Kumar, Narayajee and several others during the field excursion helped immensely to develop the initial ideas in this paper.

Received 2 June 2009; accepted 7 July 2009

A novel nesting behaviour of a treefrog, *Rhacophorus lateralis* in the Western Ghats, India

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Nest building by leaf folding is a rare behaviour in anuran amphibians, with previous reports for only two genera, the Subsaharan African *Afrixalus*, and Central and South American *Phyllomedusa*. This communication reports a specialized nest building behaviour of an Indian treefrog *Rhacophorus lateralis*, which was observed in natural habitat at Kalpetta in Wayanad District, Kerala. This behaviour of leaf folding is the first report in the family Rhacophoridae, and in the Asiatic amphibians. Nesting behaviour of *R. lateralis* is unique among *Rhacophorus* – a purse-like nest is made over water by folding a single leaf around the egg mass (embryos and translucent foam) by the female alone after oviposition. The function of this parental investment is to prevent desiccation of eggs in open sunlight. This paper also documents the multiple leaf nesting behaviour of other two species of this genus, *R. calcadensis* and *R. pseudomalabaricus*, and the previously documented nesting behaviour of *R. malabaricus* using more than one leaf.

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Keywords: Leaf folding, leaf nesting, *Rhacophorus lateralis*, treefrog, Western Ghats.

IN addition to typical aquatic habitats, anuran amphibians deposit eggs in a wide range of places including underground[1], arboreal foam nests[2], tree holes[3] and stream banks[4]. Among the 262 anuran amphibians reported from India[5], above-ground nest construction using multiple leaf is known only in *Rhacophorus malabaricus*[6].

Rhacophorus lateralis is a small sized Rhacophorid treefrog (snout to vent size-male: 28.6–30.1 mm, $N = 5$; female: 33.5–34.8 mm, $N = 3$) having bright green or light reddish-green dorsal colour with a prominent golden yellowish streak from snout along the side of head to near the vent. Scientific knowledge on *R. lateralis* is sparse other than the original description based on a sole preserved animal[7], followed by rediscovery after a gap of more than 100 years from the Western Ghats of Kerala[8] and Karnataka[9]. *Rhacophorus lateralis* is an endangered species[10], thus a better understanding of the breeding biology of this frog is critical for its conservation management.

A breeding population of *R. lateralis* was observed over two breeding seasons during which courtship, mating and leaf nesting behaviour were studied. The primary objective of this communication is to document leaf nest construction behaviour of *R. lateralis* and determine the possible function of this behaviour based on field observations and laboratory studies. The complete sequence of courtship and mating behaviour of this species is beyond the scope of this communication. This study is based on observation of 65 nests, including nine sequences from pair detachment after oviposition to completion of leaf nesting.

The study was conducted during 2000 and 2005 breeding seasons (June–September) at Kalpetta (11°36′N, 76°05′E; 980 m asl), Wayanad District, Kerala. Amplexed pairs were located by active searching guided by choruses or by making repeated observations of single females until they mated. Amplexus is axillary and duration of egg laying varies from 35 to 50 min ($N = 9$). Fieldwork was undertaken at a natural breeding pool between 19:00 and 23:00 h using a dim or red flashlight. The pool was 3.2 m wide and had a maximum depth of 0.9 m. Grasses, low herbs (*Ludwigia* sp., *Lantana* sp., *Chromolaena* sp., etc.).