Defining a space-based disaster management system for floods: A case study for damage assessment due to 1998 Brahmaputra floods

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A proto-type space-based disaster management system (DMS) has been organized with comprehensive database design, space-based near real-time monitoring/mapping tools, modelling framework, networking solutions and multi-agency interfaces. With the appropriate synthesis of these core elements, a system-definition of the frame-work of a DMS has been arrived at, in terms of developing a methodology towards damage assessment due to 1998 Brahmaputra floods. The limited validation experiments carried out in consultation with local level functionaries reveal that the experimental results on damage to agricultural crops due to floods are in conformity with field conditions. Still, there is a gap existing between the estimates arrived at and the estimates derived from conventional methods. It is herein that a concerted effort towards achieving absolute accuracy is called for. The conceived DMS ultimately aims at providing a holistic design and development of an information system, mainly to support the information needs for preparedness, prediction, damage assessment, rehabilitation and research; networking, mainly to be able to speedily provide access to the information system at any point of time from any place and decision, making, to support speedy and efficient decisions being taken, actions being implemented along with feedback mechanisms.

WITH about 40 million hectares flood-prone areas coupled with the average annual damage to the extent of Rs 500 crores and affecting 10 per cent of total population, floods have been the most severe natural disaster in India. Ironically, the flood-affected areas have increased 3 times since 1960. The average total damage incurred presently is about six times that incurred in 1950s. Generally 60% of the total damage due to floods is in the states of Assam, Bihar, Uttar Pradesh and West Bengal[1]. Ever-increasing

catastrophic flood profiles in the country call for utmost attention at all levels.

Brahmaputra, the biggest river in the Indian subcontinent, is uniquely characterized by its narrow sized valley coupled with the steep slopes and transverse gradient along with catchments experiencing the highest rainfall and loading heaviest sediments, which are driven mainly due to deforestation and unsustainable agricultural practices. The recurring floods leave a trail of deaths, destruction and damages to existing infrastructure, including roads, bridges, embankments, irrigation canals, buildings and crops. Due to information gap during critical times and absence of precise damage assessment, the State and Central mechanisms are unable to address the flood management-related issues more judiciously and efficiently.

Recent years have witnessed tremendous developments in the areas of space-based remote sensing applications with increasingly improved spatial, spectral and temporal resolutions, database technology, viz. Geographic Information System (GIS), modelling (simulations, finite element methods, digital elevation modelling, etc.) and networking. Space technology, being at the core of these developments, offers critical and synergistic potentials towards developing the operational framework for space-based Disaster Management System (DMS). Especially, space remote sensing provides valuable and unbiased inputs on inundation/damage due to floods on near real time basis, in remote and inaccessible areas[2]. A system-definition of the framework of a DMS is of utmost importance, appropriately incorporating elements of an information system to support the needs for preparedness, prediction, damage assessment, rehabilitation and research. Networking is essential to enable speedy access to the information system to support efficient decision-making and follow-up actions. Taking into account the critical role that space could play, synergistically coupled with contemporary technologies, a DMS for floods has

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been conceived with the core elements which include database design, near real-time monitoring/mapping tools, modelling framework, networking solutions and multi-agency interface development.

The current study, carried out for 1998 Brahmaputra floods, is aimed at establishing the synergistic coupling between space and the relevant conventional technologies with multi-agency interface to evolve a DMS for flood damage assessment. The three districts, namely Dhemaji, Morigaon and Dhubri of Assam, in Brahmaputra valley were covered under the study.

The study area

Amongst the largest river in the world, total length of Brahmaputra from its origin in a glacier east of Manasarovar to its out fall at Bay of Bengal is 2880 km, out of which 918 km is in India. In Assam, the length is 640 km and its average width is just 80 km. Although two-third of its length and more than half of the catchments are in Tibet, about two-third contribution of its flow is from the drainage area in India[3].

Brahmaputra river valley in Assam from Kobo to Dhubri is joined by about 20 important tributaries on its north bank and about 13 on its south bank. Its major north bank tributaries are Subansiri and Jia Barali, which flow in from Arunachal Pradesh, and Pagladiya and Manas, which flow in from Bhutan. Its major south bank tributaries are the Burhi, Dihing from Arunachal Pradesh, Dhansiri from Nagaland and Kapili from Assam's Karbi Anglong district. The drainage area of the north bank has been getting more intrusive rainfall and has stable soil with steep land slopes. Consequently, these rivers carry large amounts of silt and bring flashy floods.

The meteorological conditions in the catchment of the Brahmaputra in Tibet and in India are different and lie in different climatic zones. The zone in Tibet comprises plateau regions and that in India comprises hilly ranges and plain areas of Assam valley. The drainage area is also subjected to cyclonic storms originating in the Bay of Bengal, particularly during the pre-monsoon period of May and June and later part of September, besides regular monsoon from June to September[4].

The mean annual rainfall over the whole catchment, excluding Tibet and Bhutan is about 2300 mm. The mean annual rainfall over the sub-catchments varies widely from 2590 mm in Dihang catchment to 1735 mm in Kopili sub-catchment. In the northern part, monsoon rainfall accounts for less than 50 per cent of the annual rainfall, the pre-monsoon around 35 per cent and winter rain around 10 per cent. In the rest of the catchment towards the south, 60 to 70 per cent rainfall occurs during the monsoon period and 20 to 30 per cent in pre-monsson season and a small amount during winter[4].

The available data show clearly that the average area affected by floods during 1990s was higher than in 1980s.

Floods in the Brahmaputra valley have been aggravated due to change of course of rivers, changes in bed-topography, heavy landslides, siltation, etc. Floods have also been aggravated by considerable degradation of catchment areas by mindless earth cutting and road building activities all over, perceptible decline in the forest cover, Jhum cultivation and other factors. The level of the bed of the Brahmaputra by all calculations has gone up appreciably due to heavy deposit of silt, leaving very little facility for quick drainage during peak monsoon period. The bed of the Brahmaputra has gone up by as much as 4 m in some parts, which is certainly alarming[4]. And it has been carrying the highest load of sediments – about 648 mt per year – by any river in the sub-continent.

Added to flood is the associated problem of erosion which has assumed serious proportions. It is estimated that more than ten lakh ha of land have been eroded in Assam, followed by 8.15 lakh ha in Meghalaya, 5.08 lakh ha in Nagaland, 1.08 ha in Tripura and 0.14 lakh ha in Manipur by water erosion. Rate of erosion in the Brahmaputra catchment, 953 ton per sq km per year, is the highest in any catchment system in the whole world[4]. Many thousands of hectares of valuable tracts have been eroded by the Brahmaputra and Barak and their tributaries in the recent past. Population has been growing rapidly in the plains. The steep increase in population has forced the people to encroach riverine areas resulting in constrained waterways, which also increases sedimentation, and in turn increases the floods of higher intensity. Abandoned channels and horseshoe lakes, which would otherwise absorb at least the initial impact of floods, have been reclaimed.

DMS for flood damage assessment

The most important requirement is to define the DMS with its overall requirements of users at various levels and the delivery mechanisms which could provide the services effectively towards monitoring, forecasting, warning, assessment, prediction and reduction of natural disasters as well as establishing an appropriate feedback mechanism with conventional system.

The information required by disaster managers in each of the critical phases of disaster management, which includes mitigation and preparedness, response and recovery/relief needs to be met with. The elements of such a DMS, therefore, will consist of (i) database design; (ii) near real time monitoring/mapping; (iii) modelling framework; (iv) networking solutions, and (v) multi-agency interface as depicted in Figure 1.

Database design

The database will include the themes related to hydrology, topography, administrative units, socio-economic, infra-

structure, land use/land cover, soils and drainage (Table 1). Though it is essential to have Digital Elevation Model (DEM), drainage and soil layers, certain operational constraints such as restriction on close contour data and non-availability of soil maps on 1 : 50,000 scale did not allow to include these layers in the digital database. A reliable land use/land cover map when compared with the inundation map of the same area in a GIS environment can give the scientific basis of estimates of loss of various resources. The onset and duration of inundation of a land use category would indicate the extent of loss in financial terms. This estimate being objective and scientifically based is more authentic over conventional techniques.

Landuse/landcover

Landuse/Landcover maps for three flood-prone districts, viz. Dhemaji, Dhubri and Marigaon having geographical area of 2637 sq km, 2676 sq km and 1559 sq km, respectively, were generated using digital classification techniques with kharif and rabi season data. The study areas were deliberately chosen to represent the diverse terrains of the basin. While Dhemaji district represents the typical terrain characteristics of upper Brahmaputra, Morigaon district replicates the middle Brahmaputra and Dhubri represents the plain land of lower Brahmaputra.
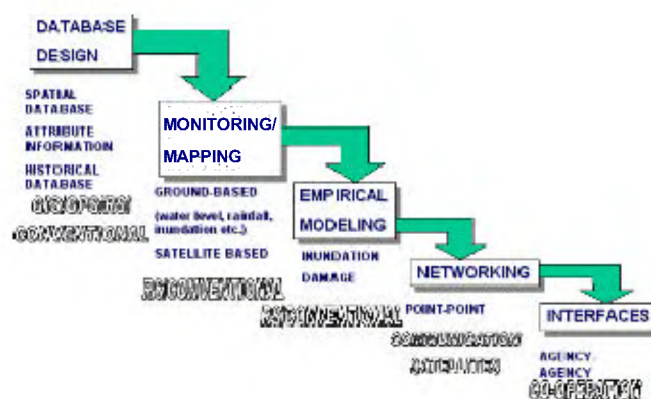

Figure 1. DMS elements.

Geo-referencing

As a precursor all the satellite data have to be geo-referenced with respect to Survey of India (SOI) topographical sheets. This helps in the geometrical correspondence of all the individual layers (satellite data and other collateral maps). By using about 20 topo-sheets, rectifying the topo-maps with SOI coordinates, a digital cartographic database was created. This was used for geo-referencing all the satellite data.

Classification

The themes (present in the satellite data of the districts) are replete with utmost spectral confusion in the form of a conspicuous red wash almost in the entire image space. This had happened owing to high fertility and moisture content of the soils. So, unlike other areas, special care was taken in the study areas to classify the data into themes with reasonable accuracy. All the spectrally similar entities were masked and stratified and then classification was launched on the individual stratum. One season data (past rabi or kharif) were taken from the Assam Remote Sensing Centre (ARSAC) archive. Rabi and kharif classified data were aggregated to get a round-the-year picture. The result of land use/land cover classification of the three districts are shown in Table 2.

Digitization of Thana maps

All the relevant thana maps having the mouza (village) boundaries shown on it, prominent cultural features like roads, rails, etc. taken from the topo-sheets were digitized, edited and vector files were created. Administrative boundaries of districts, mouza and villages of each district are extracted from 1 : 63,000 topo-maps and Thana maps and stored in vector format. Topo-maps are procured from Survey of India and Thana maps from land records, Assam. Similarly transportation networks such as road and rail were extracted from 1 : 50,000 topo-maps and stored in vector format as separate layers. This was finally integrated on the land use/land cover map. This is vital for

Table 1. Theme-wise data sources

Theme	Data layer
Hydrology	Flood maps water levels, historic flood boundaries
Topograhy and geomorphology	Elevation contours, drainage maps
Boundaries	Administrative boundaries (district, Mouja, village)
Socio-economic	Population and economic status and census data
Manmade features, communication levels (telephone/STD)	Road, rail networks, hospital, bridges, settlements, police stations
Land use/land cover	Land use/land cover and its attributes information
Soil map	Soil texture/structure/permeability
Drainage	Order, density, etc.

Table 2. Digitally classified land use/land cover maps

Name of category	Dhemaji Area in ha	%	Dhubri Area in ha	%	Marigaon Area in ha	%
Kharif only	1,18,682	46.24	49,086	17.61	49,804	31.78
Rabi only	–	–	8059	2.89	7756	4.95
Double crop	19,175	7.47	63,123	22.64	18,594	11.86
Residual fallow	15,015	5.85	12,454	4.47	6714	4.28
Orc + habit	29,392	11.45	23,544	8.44	37,390	23.86
Dense forest	14,035	5.47	27,230	9.77	208	0.13
Open forest	993	0.39	16,347	5.86	18,595	11.86
Degraded forest	3455	1.35	10,937	3.92	2531	1.62
Marsh	3770	1.47	2163	0.78	2487	1.59
Water body	12,038	4.69	19,314	6.93	14,444	9.22
River sand	30,233	11.78	29,240	10.49	2174	1.39
Grass, scrub and others	9903	3.86	17,301	6.21	7134	4.54
Total	2,56,691	100.00	2,78,798	100.00	1,67,831	100.00

Table 3. Digital database details

Information layer	Source	Storage format
Administrative boundary district/Mouza village/ town	1 : 63,000 topo-maps and Thana maps from land records	Vector
Transportation network road/rail	1 : 50,000 topo-maps	Vector
Land use	Satellite data	Raster

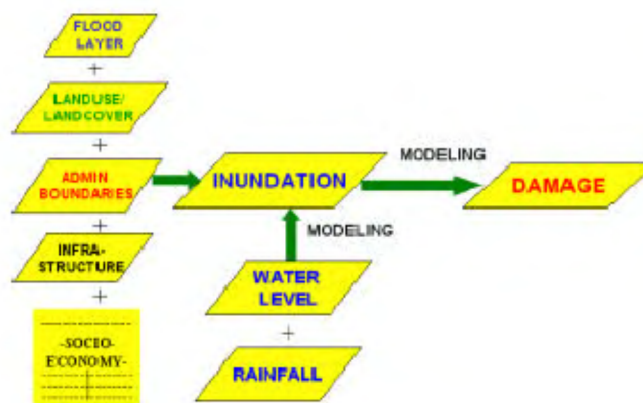**Figure 2.** Integration of themes for damage assessment.

the actual assessment of the flood damage on a territorial unit.

Digital database creation

A detailed digital database is a pre-requisite for flood damage assessment. This includes administrative boundaries, socio-economic data, land use and transportation network, etc. of the various layers were stored in the GIS environment. Table 3 shows details of digital database. A digital database was prepared for three districts in Assam, namely Dhemaji, Marigaon and Dhubri for the study. The database was created using ARC/INFO & ERDAS IMAGINE software packages.

Remote sensing based inundation mapping/monitoring

The methodology for near real-time flood damage assessment is shown in Figure 2. Cloud-free satellite data prior to flood season were procured and rectified using topomaps. These rectified satellite data sets were used as master image for rectifying the other data sets. The satellite data procured during the flood season are geometrically rectified and enhanced. Subsequently the image is classified for the extent of inundation and flood inundation maps were prepared. The flood boundary was delineated and extracted from the classified image. The extracted

flood boundary was integrated with GIS data layers that have been already created in ARC/INFO to estimate the flood damages.

Near real-time flood monitoring/mapping

Indian Remote Sensing satellites are being used for obtaining information on flood inundation areas and estimation of flood damages. The current IRS series (IRS-1B, IRS-1C, IRS-P3 and IRS-1D), which collect information in optical region of the electromagnetic spectrum at different spatial resolution, provide valuable information on flood situation. IRS WiFs sensor, which has a wide swath of about 800 km proves to be very effective in monitoring floods in the entire basin/State. The flood-affected areas in Assam are covered by a single WiFS scene at 188 m resolution (Figure 3). The 3-day revisit of combined IRS-1D and IRS-1C WiFS data results in good temporal coverage in addition to IRS-P3 which revisits at every five days over any specific area during the flood months. Whereas, LISS III with a spatial resolution of 36.5 m and PAN with a spatial resolution of 5.6 m provide more detailed information on the ground conditions (Figures 4 and 5).

Figure 3. 1998 Brahmaputra floods – Basin-wise monitoring.

Figure 4. 1998 Brahmaputra floods – Damage to road network (part of Marigaon district).

Figure 5. 1998 Brahmaputra floods – Damage update using PAN (part of Marigaon district).

During the year 1998, most of the data used for flood mapping are of WiFS, as it covers the Brahmaputra river in Assam 66 times during flood months (June–September). During persistent cloud cover over the basin RADARSAT Wide Scan SAR (microwave) data were acquired through a special arrangement. Two Wide Scan SAR RADARSAT scenes cover the entire Brahmaputra river in Assam. NRSA Data Centre (NDC) acquires this data through FTP from Canada to avoid delay in physical transfer of the data. During the flood season of 1998, the Brahmaputra basin was covered by IRS-1B (30 scenes of which one was cloud-free), IRS-1C (26 scenes with 2 cloud-free scenes), IRS-1D (32 scenes with 3 being cloud-free) and IRS-P3 (8 scenes with one being cloud-free). Table 4 gives details of flood inundation for the three districts derived from satellite data during the peak flood on 8 September 1998.

Modelling framework for damage assessment

Modelling with inputs from remote sensing and GIS data on inundation, water level and rainfall data at different hydrologically strategic locations in the river basins/sub-basins was developed to arrive at inundation profile and crop damage (Figure 6).

Inundation modelling

Because of persistent cloud cover during the flooding season, it is important that inundation profile could be developed even if cloud-free satellite data are not available. This is possible only if inundation is derived from water level and rainfall in their respective catchments using historical database. The historical data of water level and rainfall along with inundation for the three dis-

tricts were collected from Central Water Commission (CWC) and Assam State Agriculture Department. A multiple regression analysis was carried out to estimate the total inundated area as well as inundated crop area. The results of regression analysis are depicted in Figure 7 a–c for Morigaon district. Figure 7 b depicts the results of multiparameter analysis of flood inundation correlated with water level and rainfall at different monitoring stations and Figure 7 c depicts similar results for inundated crop area (ICA). Such analysis was carried out for Dhubri and Dhemaji districts also. It is important to note that there is a significant relationship between water level/rainfall and inundation (also see Table 5). The important aspect here is the number of monitoring stations and to what extent this represents the catchment. In Dhemaji district, for example, there are six monitoring stations, two across Brahmaputra, two across Ghai river and two across Jiadhal river. With this data, the relationship between water level/rainfall and inundation improved the confidence level, co-efficient of determination being 0.9 (Table 5). However, these results need to be validated with data from CWC and State departments.

Modelling for crop damage assessment

The estimation of damage from inundation profile due to different flood waves can be done through modelling using Inundated Crop Area (ICA) appropriately combined with crop calendar, crop yield, cost of cultivation, water level and rainfall. The damage assessment is given by:

$$CD(i, j) = \sum_{i=1}^{n} D(i, j) * ICA * LF, \qquad (1)$$

where CD is crop damage (in rupees); i is District; j is Crop type; D is Damage/ha (Rs/ha); ICA is Inundated Cropped Area (ha); LF, Loss factor (%).

The damage D is a function of crop yield and cost of cultivation as given by

$$D(i, j) = (Cci + Yi), \qquad (2)$$

where Cci is Cost of cultivation (Rs/ha) and Yi is Crop yield (Rs/ha).

The crop data, which were fed into the models are given in Table 6. The model results on crop damage due

to different flood waves in the three districts are presented in Figure 8.

In case of Dhemaji district, flood continued for long duration and hence all the submerged crops were lost. This is reflected in the results also. It is interesting to note that crop damage estimated from IRS WiFS-derived ICA is comparable to crop damage derived from ICA State Government data and ICA model (based on water level and rainfall). In case of Morigaon district, the estimate was Rs 15 crores from IRS WiFS-derived ICA, while that derived from State Government ICA data is about Rs 25 crores. Thus there is a need that these figures be validated. With the inclusion of cost of cultivation data into the models, the crop damage due to the flood goes up significantly. Damage to the infrastructure has not been attempted mainly because of complicated cost factors associated with various infrastructures damaged during the floods.
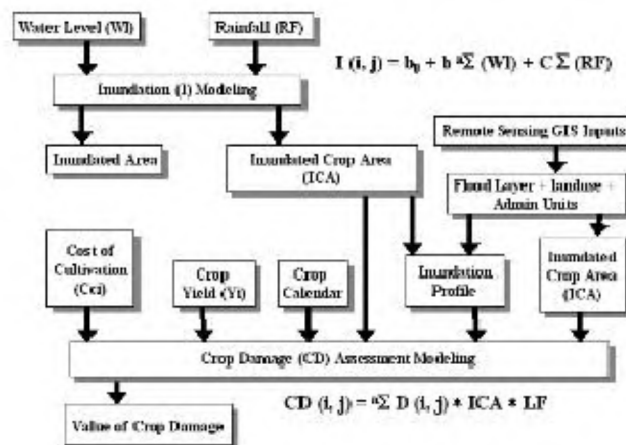

Figure 6. Empirical flood model.

Table 5. Results of multiple regression analysis carried out between inundation (I) and inundated cropped area (ICA) vs water level and rainfall

Study area		Regression equations	Correlation coefficient
Morigaon	(i)	I = – 100.056 – 0.885 WL1 + 0.193 RF1 + 3.066 WL2 – 0.0478 RF2	0.71
	(ii)	ICA = – 116.701 – 0.86 WL1 + 0.1499 RF1 + 3.194 WL2 – 0.0674 RF2	0.68
Dhemaji	(i)	I = 153.71 + 2.91 WL1 + 0.299 WL2 – 0.48 WL3 – 3.0 WL4 + 0.145 RF	0.94
	(ii)	ICA = 53.37 + 0.81 WL1 + 0.04 WL2 – 0.13 WL3 – 0.73 WL4 + 0.06 RF	0.96
Dhubri	(i)	I = – 896.58 + 30.96 WL – 0.14 RF	0.76
	(ii)	ICA = 256.1 + 18.8 WL – 0.06 RF	0.70

WL, Water Level; RF, Rainfall.

Table 4. Data on flood inundation based on the analysis of 8 September 1998 peak flood using satellite data

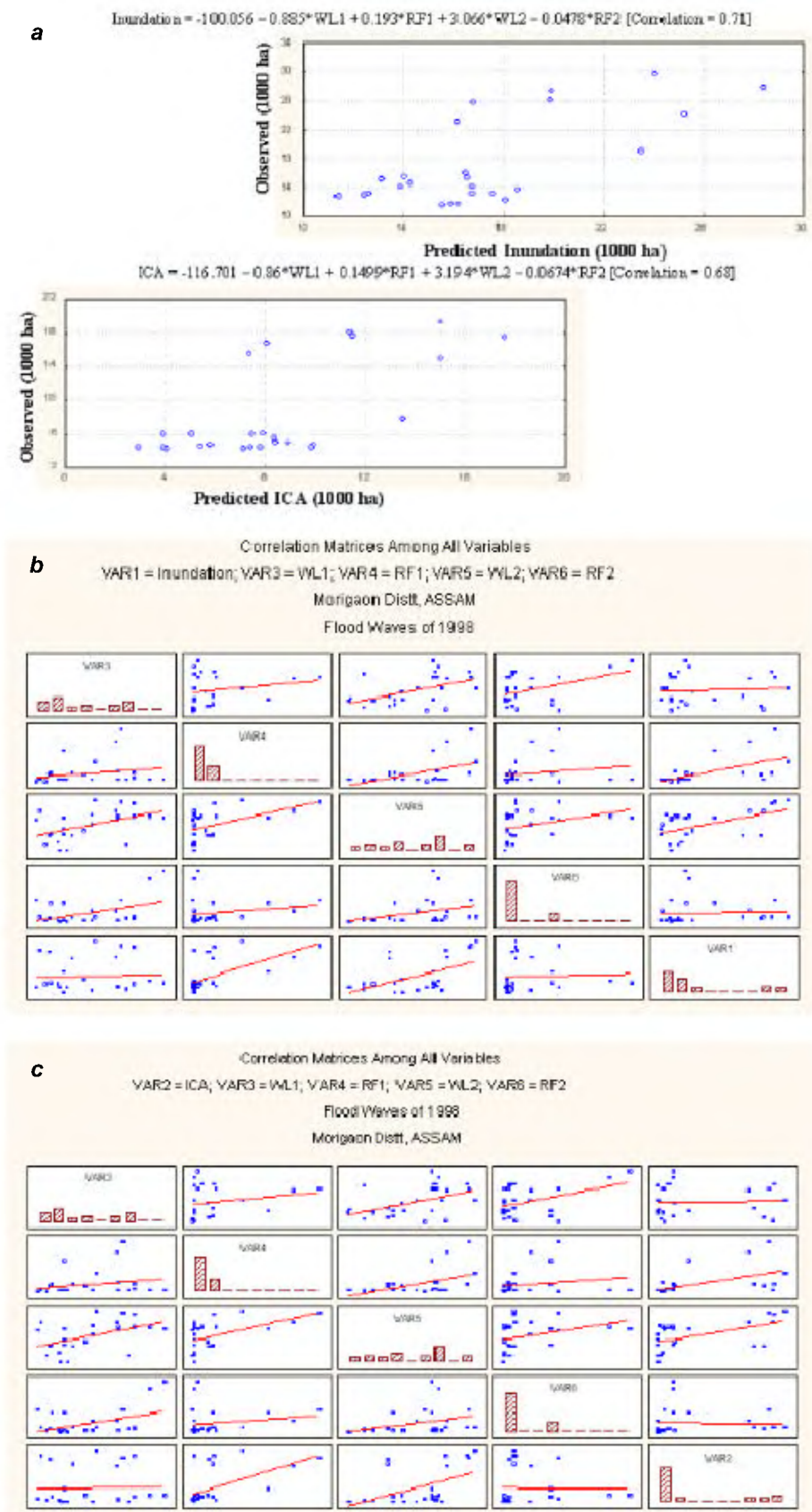| District	Area inundated (in ha)	Crop area affected (in ha)	No. of villages marooned
Dhemaji	41,040	34,946	379
Marigaon	51,068	28,028	465
Dhubri	1,03,197	55,715	545

Figure 7. *a*, Observed vs predicted inundation and ICA values (1998) Marigaon district, Assam. *b*, Multiparameter analysis of inundation profiles. *c*, Multiparameter analysis of ICA profiles.

Table 6. Data on crop and cost aspects used for modelling

| District | Normal yield (kg/ha) 1996–1997 | | | | |
	Sali paddy winter rice	Ahu paddy autumn rice	Bao paddy summer rice	Jute	Sugarcane
Dhemaji	1272	601	1701	1537	39389
Morigaon	1297	644	1823	1929	38440
Dhubri	1334	550	1634	1175	39389
Crop calendar	(June–July) to (Oct–Nov)	(Mar–Apr) to July	(Mar–Apr) to (Nov–Dec)	(Feb–Mar) to (July–Aug)	(Apr–May) to (Dec–Jan)

Cost of damage of paddy, Rs 8505/ha; Cost of cultivation of paddy, Rs 4250/ha.
Source: Agricultural Department (Govt of Assam).

Table 7. Communication elements in the project

Task	From	To	Mode	Remarks
Water levels and forecast	CWC	ARSAC, Guwahati	Fax/messenger	Operational
Same as above	ARSAC, Guwahati	NRSA	Fax/e-mail	Operational
Flood inundation vector/topo-map	NRSA	ARSAC, Guwahati	NICNET	Operational
District-wise damage assessment	ARSAC, Guwahati	District Commissioners	NICNET/Messenger	Experimental
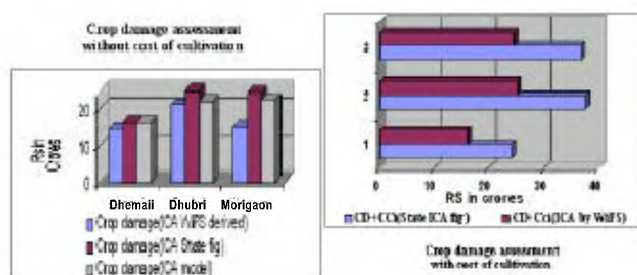
Figure 8. Model results of crop damage assessment.

Networking solutions

Data communication is the central part of DMS due to the distributed nature of the system elements. The remote sensing data have been acquired from several data providers, brought to a processing centre, the analysis routed through the State Remote Sensing Centre and ultimately passed onto district administrators for decision making. Each of these elements involves computer and digital data processing at different geographical locations. Since there is no existing network connectivity between all these locations, the NICNET facilities have been used. The space-based communication is indispensable to meet the real-time data transfer needs from space agency to user locations at remote places. In the present case, the major information contents and mode of transfer of same are as shown in Table 7.

The delivery of digital flood layer overlaid on intersected land use/land cover and administrative boundaries maps (as shown in Figure 9) has to be on near real-time basis. The file transfer from NRSA to ARSAC, Guwahati was routed through existing high speed NICNET facility between Hyderabad and Guwahati. The last leg of data transfer from ARSAC to the District Commissioner's office was done with the existing low throughput (1 kbps) NICNET. However this mode of delivery is still acceptable compared to the one-day delay in case of the maps being sent physically.

Multi-agency interface

Considering the interconnections at different locations/agencies to execute the DMS for flood damage, working level inter-institutional mechanisms were established among ISRO/DOS, CWC, ARSAC, NIC and State Government departments. The organizational interface consisted of NRSA, Hyderabad identified with activities related to (i) generation of pre-flood cloud-free satellite data, (ii) generation of flood layer on near real-time basis, and (iii) area statistics related to inundation; Regional Remote Sensing Service Centre (RRSSC), Kharagpur responsible for (i) generation of land use/land cover map, (ii) digitization and integration of various themes such as land use/land cover, administrative units and infrastructure; EOS/NNRMS, ISRO Headquarters for development of inundation and damage assessment models; ARSAC as the active interface between ISRO/DOS and Assam State Government. Along with this, ARSAC also participated in data analysis, map generation, co-ordination with district level officials for collection of collateral information with CWC and NIC.

Space-based DMS for floods

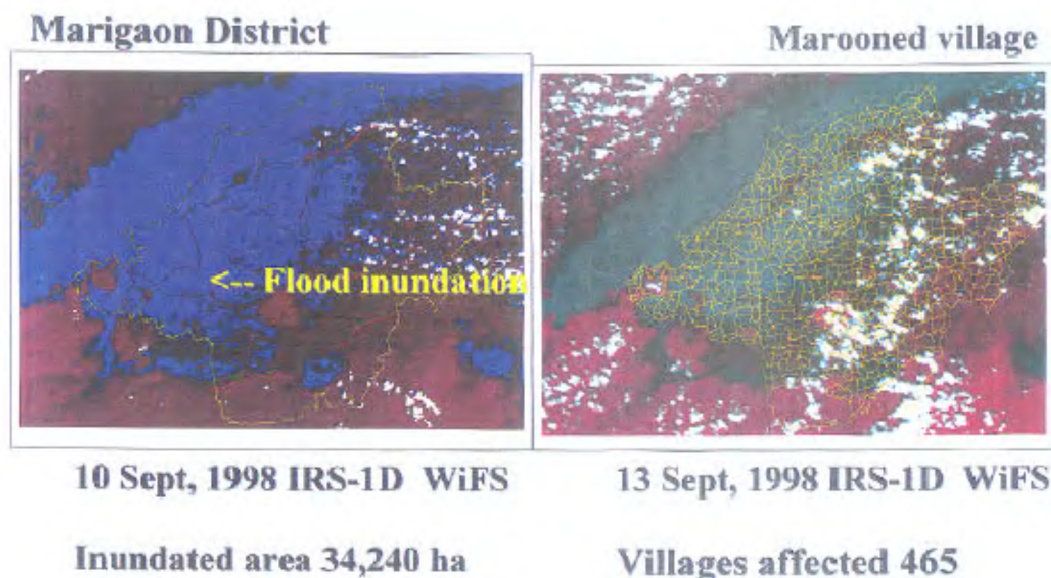In the present study on damage assessment due to floods, the core elements of DMS have been synthesized. This

10 Sept, 1998 IRS-1D WiFS   13 Sept, 1998 IRS-1D WiFS

Inundated area 34,240 ha   Villages affected 465

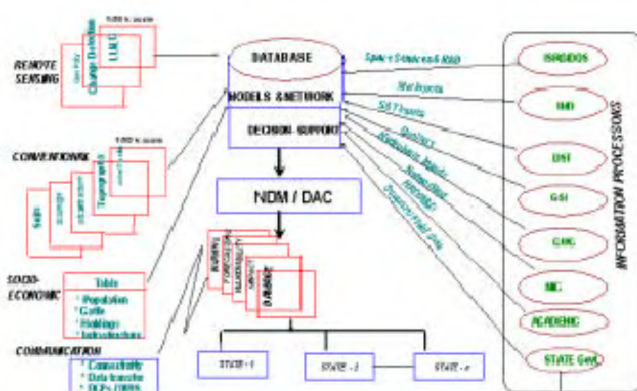**Figure 9.** 1998 Brahmaputra floods – Inundation extent.

Figure 10. DMS: Possible framework.

could be replicated elsewhere for similar objectives and with appropriate people's participation, holds the key to combat natural disasters. Taking into account these aspects, a proto-type DMS framework could be envisaged as given in Figure 10 to meet the information needs of Central and State Governments.

The most difficult user requirement is information dissemination on near real-time basis, particularly for events such as floods, cyclones and earthquakes. It is here that remote sensing systems (both optical and microwave with high repetitively and optimal swath) could serve as an efficient monitoring tool. The space, ground and user segments have to be oriented to use such tools for disaster management needs.

1. Compendium of Environment Statistics, Central Statistical Organization, Department of Statistics, Ministry of Planning and Programme Implementation, Govt. of India Publication, New Delhi, 1997, pp. 115–120.
2. Kasturirangan, K., Chandrasekhar, M. G., Nageswara Rao, P. P., Srivastava, S. K., Ganesh Raj, K. and Sebastian, M., in Proc. United Nations/IAF Workshop, 28 September–1 October, Oslo, Nowray, 1995, pp. 135–166, (eds Jasentuliyana, N. and Mayer, S.), United Nations, Office of Outer Space Affairs, PO Box 500, A-1400, Vienna, Austria.
3. Master Plan for Brahmaputra Basin, Summary, Recommendation, Programme and Outlays, Brahmaputra Board, Ministry of Water Govt of India, 1986.
4. Report Centre for Science and Environment, New Delhi (eds Anil Agarwal and Sunita Narain), 1991.