A GRASS-GIS-Based Methodology for Flash Flood Risk Assessment in Goa

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Executive Summary

Recurring floods in Goa cause damage to both property and life. After the 2 October 2009 flash floods in Canacona Taluka, South Goa, the Government of Goa constituted a committee (Canacona Flash Floods Study Committee) to study the flood event and suggest measures to minimize damages occurring from similar episodes in future.

The committee recommended the developing of a methodology for flood risk assessment and warning during an intense-rainfall event which can be implemented elsewhere in Goa with the help of graduate students. This requires the analysis of topography for river flow (watershed analysis) and converting rainfall to river flow (discharge calculation). The watershed analysis is based on a free and open source GIS called GRASS GIS. It calculates the watershed properties (watershed areas, stream network, slope, etc.). It also identifies and delineates areas nearest to the stream channel, the ones most likely to be affected by flash floods (flood-prone areas).

Based on the discharge calculations, a simple method to give warning of the possible occurrence of flash flood due to intense-rainfall events is also developed. A simple but widely used hydrological model, called *rational method*, is used to calculate the peak discharge in the selected stream. Based on this method, a flood watch algorithm is derived, which uses rainfall intensity data from the nearest Automatic Weather Station (AWS).

The method developed uses free and open software tools and requires a bare minimum of input data, namely, topographic data (Digital Elevation Model, DEM) and rainfall data, both of which are available free of cost in the public domain. Its viability is tested for the flash flood of 2 October 2009 in the Talpona river. The method is mainly aimed at graduate students of Goa and it is hoped that the framework will be further strengthened in the future, by incorporating advanced hydrological flood forecasting models. Thus, this study aims at being a starting point to have in place a full fledged flash flood assessment and forecasting system for Goa.

1 Introduction

1.1 Background

The west coast of India is one of the maximum rainfall regions of the country, with $\sim 90\%$ of the rainfall occurs in the monsoon (June–September). The orography of the coast and heavy rainfall makes the region flood-prone during intense-rainfall events. These intense-rainfall events occur frequently on the coast, the probability of these episodes being maximum between latitudinal band 14°–16° N and near 19° N (Francis and Gadgil, 2006).

The state of Goa (Figure 1), (15°–16° N and 73°–75° E) lies in the above mentioned band of intense rainfall-event-prone area. Overall the climate and geography of Goa is typical of the west coast of India. The heavy rainfall experienced here is owing to the presence of Sahyadris. The Sahyadri mountains (also known as the Western Ghats) run along the coast. They rise to a height of about 1000 m. The peaks of the Sahyadris straddle a very narrow coastal plain (Figure 1) (average width of the plains is ~ 50 km). The coastal plain itself is dotted with hills, and valleys through which rivers originating from the hills and slopes of the Sahyadris flow eventually to drain into the Arabian Sea. The source of water in these rivers is heavy rainfall on the slopes and hills of Sahyadris due to the orographic lifting of moisture laden winds coming inland from the Arabian Sea in the Indian Summer Monsoon. This small geographical area of the coastal plain and heavy rainfall on the hills makes the region flood-prone.

In the last decade, there were at least four major flood events (floods of 2000, 2005, 2007 and 2009). The frequent floods caused much damage to the state. The flash flood of 2 October 2009 was a severe one affecting the Canacona Taluka of South Goa district. The floods caused extensive damage to the Canacona Taluka: 2 lives were lost along with an estimated damage of property worth 100 crore rupees. In the wake of this flood, the Government of Goa constituted the Canacona Flash Floods Study Committee (CFFSC) under the chairmanship of Dr. S. R. Shetye, Director, National Institute of Oceanography (CFFSC, 2009). CFFSC (2009) determined that the flash flood was a direct consequence of the intense-rainfall event of 7-hours (between 9:30 AM to 4:30 PM of 2 October 2009), where 271 mm of rainfall occurred in the Canacona Taluka (CFFSC report can be downloaded from NIO's website (`www.nio.org`)).

The CFFSC was also mandated by the Government of Goa to suggest measures to be adopted in Goa to minimize damage arising from similar episodes in future. The specific recommendations in this regard to develop a methodology to identify vulnerable areas are outlined below (from CFFSC, 2009):

(a) The areas vulnerable to mudslides should be mapped and site-specific disaster management plan to face them should be in place at each location with high vulnerability.

(b) Areas with high vulnerability to flooding due to an intense-precipitation event should be identified and a disaster management plan should be evolved at locations that are particularly vulnerable.

(c) A mechanism for keeping a careful watch should be in place whenever a situation arises with high potential for an intense-precipitation event in a vulnerable area. The Meteorological Centre of the India Meteorological Department (IMD), Panaji, should form the nerve centre of such a watch.

(d) The State of Goa should make IMD's "Cyclone Warning Dissemination System" operational in the state.

Further, the CFFSC recommended that:

> In order to enlarge the state's awareness of damage from precipitation events, the above should be carried out using the services of faculty and students from Goan undergraduate and post-graduate institutions, and then circulated widely amongst local policy and decision makers. To assist this process, the NIO Team should prepare one report on one site on each of the two aspects described in (a) and (b). These reports could then be used as models for carrying out case studies by undergraduate and post-graduate institutions in Goa to examine other vulnerable locations.

This report addresses the above specific recommendation (b). A method aimed at graduate students is developed for the flood risk assessment in Goa.

1.2 Challenge

Rivers are an important part of the hydrological cycle; they route water from rainfall over land surface to the sea. The water in the rivers (streams) flows through a river channel, which is bounded by natural (sometimes artificial) embankments. The river (stream) channel is etched in a relatively flat surface of land, formed by sediments brought by the river. This relatively flat surface is known as floodplain. Depending upon the weather, generally, the flow in the rivers is contained within the stream channel. During intense-rainfall events (in the monsoon), however, rivers flow in full (peak flow) and water spills over to the floodplain. A flood flow is defined as any high flow that spills over the embankments along the river (Chow et al., 1988). This flooding is a natural event and occurs almost every year in a heavy rainfall region such as the west coast. Occasionally (as on 2 October 2009), extreme flood flows (magnitude much greater than peak flow) occur during particular intense-rainfall events; the terrain cannot route the resulting heavy runoff efficiently and promptly, causing damage to life and property because of heavy discharge and water inundation.

Flash floods can occur within minutes due to extremely high rainfall intensities, and are different from the general floods occurring due to rainfall events of higher duration (days to weeks). Flash floods also tend to occur in small watersheds as compared to general floods in big river basins (Shelton, 2009).

Flash floods are caused by slow-moving weather patterns (convective systems) that generate intense rainfall over the same area. Important contributing factors include topography and soil condition: the water is concentrated into a small area without getting absorbed into the soil (Shelton, 2009). During such an intense episode almost all the rainfall is converted into surface runoff, and if runoff is not routed efficiently or in time, flooding occurs. A flash flood is defined when flooding occurs after a few minutes to less than six hours after the intense-rainfall event (see in Shelton, 2009).

This report is concerned only with the weather-related flash floods. It is worth remembering that floods can occur due to many other causes such as dam failure, drainage network and land use changes, and other geophysical calamities.

As discussed earlier, the three most important factors for occurrence of a flash flood are intense-rainfall event, topography and soil condition. Any method for flood risk methodology should resolve these three issues.

Water flows from high to low areas, hence flow directions depend upon the topography. The method requires analysis and visualisation of topographical data; a GIS (Geographical Information System) is a must for implementing it. Commercial GIS packages were straightaway ruled out because of the staggering cost and licensing issues. Further, most of the commercial packages are not flexible and cannot be customised since their source code is not available. These facts prompted us to use an open source GIS software called GRASS GIS (Geographic Resources Analysis Support System GIS), available freely on the World Wide Web (`http://grass.itc.it/`) (Neteler and Mitasova, 2002). The GRASS GIS, a highly flexible and powerful GIS, is one of the biggest open source software packages available. The GRASS GIS has many modules (both in-built and user community created) for the terrain and hydrological analysis among other standard GIS modules. It has been also used in flood forecasting and simulation (García, 2004).

Rainfall events are measured by rainfall rates, available through the weather stations. When rainfall occurs, only a certain part of it contributes to the river flow (runoff). The rest of the rainfall is either lost to the atmosphere or stored in deep ground water reservoirs. The partition of the rainfall into runoff is not constant; it depends upon many factors, such as intensity of the rainfall, infiltration rate and capacity, land cover and use. For a rain event of given intensity, the most important factor in runoff generation is the condition of soil. If the soil is wet and saturated, water cannot be absorbed in it, and almost all of the rainfall becomes surface runoff. If the soil is dry and unsaturated, most of the water is absorbed in it, only a small part of rainfall becoming surface runoff. The partition of rainfall into surface runoff and its routing through rivers, as it becomes the river discharge, comes under the discipline of hydrological modelling. Thus for estimation of flood discharge, hydrological modelling is required.

Most of the hydrological models are complex and data intensive. A simple method is required for a limited purpose of identifying areas prone to flooding. One of the simplest hydrological models, called the *rational method* is used to calculate the peak discharge during a rainfall event at a point on the stream. Peak discharge during an intense-rainfall event can be compared with the mean peak discharge (if available), and if peak discharge is much greater than the mean peak discharge, flood conditions can be expected. The rational method requires rainfall intensity and the contributing watershed area at the given point on the stream along with a parameter indicating how much rainfall contributes to the runoff. This parameter is called runoff coefficient and depends upon the watershed characteristics and soil condition.

1.3 Objective

As the data available is meager, any method employed should work with the minimum data possible. The data should also be available easily and freely. The only data used in this study are the rainfall and SRTM (Shuttle Radar Topography Mission) DEM; both are available freely on the world wide web.

In the following sections details of the method are explained using a test case for the Talpona and Galjibag rivers of South Goa, the scene of the 2 October 2009 flooding. Using GRASS GIS, a simple method to identify the low-lying areas (based on slope value) along the streams is presented. These are the best first guesses for identifying the flood-prone areas. For a precise inundation map, more complex real-time hydrological models are required, which, at present, are out of the scope of this report.

2 Data and Software

2.1 GRASS GIS

GRASS GIS is an open source and free GIS software (Neteler and Mitasova, 2002) (website `http://grass.itc.it/`). It is a versatile and flexible GIS capable of geographical data analysis and management, image processing, visualisation and graphics, and spatial modelling in multiple dimensions. It handles data in a variety of formats, which includes raster data (pixel or gridded data), vector data (e. g., line or area data), and imagery data (scanned toposheets, satellite images). Released under the GNU public license (GPL), the GRASS GIS can be used on a variety of operating systems, including Windows, GNU/Linux and Macintosh. GRASS GIS originated from the United States Army Construction Engineering Research Laboratory (USA-CERL). Now one of the largest softwares available, GRASS is an official project of the Open Source Geospatial Foundation. GRASS GIS is managed by the GRASS Development Team, a multinational team, and users can also contribute their modules.

The method is based on existing GRASS modules, especially the terrain analysis modules. The method can be implemented both in the command line interface or graphical user interface (GUI). The GRASS GUI is developed with the `Tcl/Tk` and `wxPython` packages. A future goal is to develop the analysis presented here as a software package which can be used in different operating systems such as GNU/Linux and Windows. A free and open source cross-platform utility like `wxPython` can be used to integrate all the steps and the calculations as one software package.

2.2 Geographical data: SRTM DEM

Topography plays a crucial role in determining how much and where water flows on the surface of the earth. The DEM represents the topography of a particular area: the whole region is divided into pixels (grid cells) of a given size and each pixel is given a height value connected to a standard reference. In this study the DEM used is called SRTM DEM, available freely on the World Wide Web (NASA SRTM) and covering almost all the land area ($\sim 80\%$) of the globe. The pixel size of a SRTM DEM is 3 arc-second (90 m at equator) and the average height of the pixel is stored at the centre of the pixel. Apart from SRTM DEM, other geographical data available locally such as toposheets can also be used.

SRTM DEM data is the highest resolution DEM available covering almost all the landmass of the earth. Due to certain issues with the data aquisition, SRTM DEM contains data holes (no-data), and due to this can not be used directly in the watershed analysis programs. CGIAR SRTM provides a filled version of SRTM DEM corrected data, but most probably due to interpolation errors on the west coast of India, some grid cells having negative elevation remain in the DEM. Hence, CGIAR SRTM DEM has to be corrected, which is again done in GRASS GIS. Details of SRTM data and its modification process is given in Appendix A. This modified and hydrologically corrected SRTM DEM (hereafter SRTM DEM) is able to resolve all the basins for Goa and neighbouring areas (Figure 2). If users wishe to use CGIAR SRTM (or even NASA SRTM) they can use it for the areas where data holes are not present (Data holes are present mostly in coastal areas and places having steep topographic gradients).

2.3 Climatological and weather data

Apart from the basin geometry, hydro-meteorological data is also required, because floods are a direct consequence of intense-rainfall events. In the last few years, Indian Space Research Organization (ISRO), has installed an Automatic Weather Station (AWS), which records the data at hourly resolution, at various locations spread all over the country. (See Figure 1 for AWS locations in Goa). Meteorological and Oceanographic Satellite Data Archival Centre (MOSDAC) at Space Applications Centre (SAC), Ahmedabad, archives various climatic data (including rainfall) and disseminates them through their website (`http://www.mosdac.gov.in`). The data is available freely to users who have registered themselves at their website. Rainfall data from India Meteorological Department's (IMD) rain gauges is also available from the IMD office, Panaji (with some charges for data handling) (see Figure 1 for IMD rain-gauge locations in Goa).

In Goa, there are 14 ISRO AWSs available (Figure 1). The AWS data, which has hourly resolution, can be accessed from the MOSDAC website, with a lag of 10–30 minutes. Along with the rainfall, they also record other data like wind speed and direction, air temperature, pressure, humidity, and sun shine. We have no information about the accuracy (or any studies) of other data, but the rainfall data seems to be accurate (CFFSC, 2009). The rainfall intensity can be calculated from the AWS data. This is the biggest advantage of using AWS data as the intense-rainfall events are characterised by high rainfall intensity.

3 Flood risk assessment methodology

3.1 Overall Design

The method is implemented fully in GRASS GIS environment and utilizes different modules of GRASS. The modules can be distinguished in the following three broad categories.

3.1.1 Data management

The method utilizes the data structure of GRASS GIS. The DEM is stored as raster data and the locations of AWS and flood affected places, line and area features (watershed divide and area) are stored as vector data. The GRASS GIS data management is versatile and both raster and vector data can be converted into various formats like ASCII, binary (`netCDF`) and vice-versa. The data management structure of GRASS GIS is discussed in detail in Appendix B.

3.1.2 Watershed analysis

A hydrologically corrected DEM can be used to obtain the basic basin variables such as stream network and watershed areas, including the basin outlet. The stream network map shows the route of the river (water course); knowledge of the route is essential not only to calculate the discharge at a point on the stream, but also to identify the areas lying near to the stream which would be vulnerable to flood. Another most important variable is the watershed area (catchment area) over a point in the stream. Only the amount of water that falls on this area appears at the same point in the stream. It is obvious that all the water does not appear instantly in the stream, as it has to travel from the farthest point of the watershed to the stream.

In GRASS a watershed analysis module `r.watershed` is available for watershed analysis. It uses a least-cost search algorithm designed to minimize the impact of DEM data errors. It is more accurate than the module `r.terraflow`, but this accuracy comes with the drawback of large computer time. Kinner et al. (2005) have used high-resolution DEMs like SRTM and found that `r.watershed` performed better (able to resolve streams and basins better) than `r.terraflow` in a variety of topographic features like large valleys, forest canopy mixed with barren land and watershed divide containing flat areas. A more careful approach (using case studies) is required to ascertain relative accuracy of these two algorithms, which will require stream network data (rivers digitized from toposheets). To make the watershed analysis simpler and avoid the problems associated with the existing data-holes in SRTM for Goa, we have used both the algorithms while sacrificing some accuracy. We filled the SRTM DEM with module `r.terraflow` algorithm and then used module `r.watershed` for watershed analysis. For the flood assessment method, SRTM filled with module `r.terraflow` can be used for watershed analysis using module `r.watershed` for any river in Goa.

3.1.3 Watershed analysis: results

The watershed analysis is done for Talpona river along with all the rivers of Goa and watershed areas are calculated (Appendix D). The method is able to resolve the basin geometry for all the rivers. Watershed areas presented below are calculated at the downstream points, although the user can calculate the watershed area at any point on the stream.

3.1.4 Hydrological modelling

Whenever rainfall occurs, a part of it evaporates and the remaining appears as runoff. Runoff flows through the terrain and eventually appears as flow in a river.

Conversion of rainfall into runoff and its routing through the terrain and river comes under the ambit of hydrological modelling. There are many models of varying complexities available. Complex models require extensive data and parametrisation along with certain expertise in the discipline. For this report, however, we use a simple hydrological model: this report is not aimed at hydrologists, but at graduate students of the state aspiring to investigate flash floods and its causes.

We use a model called *rational method*, one of the simplest, oldest and widely used models (Chow et al., 1988; Wanielista, 1990). It calculates peak discharge at a point in the stream during a rainfall event. This method is probably one of the most popular methods used for hydrological design purposes (i. e., building storm drainages, culverts, bridges, etc.) because of its simplicity and the fact that it does not require the dimension of flow conveyance structure (channel) to be pre-determined.

According to this method, if rainfall intensity remains constant over the time interval required to completely drain the watershed, then the runoff at the outlet of the basin is calculated as the product of the watershed area and the effective rainfall intensity (part of rainfall contributing to the discharge) over the watershed.

The above time interval is called time of concentration (T_c), which is defined as time from the start of rainfall till the time when all of the watershed is contributing to flow at the outlet. T_c is calculated as the longest travel time for a water particle to reach the outlet.

Based on the principle of mass conservation, peak discharge according to the rational method at a given point on a stream is

$$Q = CIA, \tag{3.1}$$

where Q is peak discharge (in $\mathrm{m^3 s^{-1}}$) occurring at T_c, C is the runoff coefficient (dimensionless), I is the rainfall intensity (in $\mathrm{ms^{-1}}$) for the period T_c and A is the area (in $\mathrm{m^2}$) of the watershed contribution at that point.

The basic assumptions involved in *rational method* are as follows.

(a) Rainfall intensity is assumed to be constant for a time interval at least equal to T_c. Q, the peak discharge is a function of average rainfall intensity in the time period T_c. A direct consequence of this is that the peak discharge does not result from a more intense storm of shorter duration.

(b) T_c is the time for the runoff to become established and flow from the remotest part of the watershed to reach the outlet.

(c) C and A are constants. For a given watershed area, C is the ratio of the peak discharge to the rainfall rate. It is an estimate of how much rainfall over a watershed is eventually contributed to the discharge, as all the rainfall will not appear as discharge. Some part of the rainfall is lost, either to the atmosphere or a deep ground water reservoir. For example, it is quite possible that for a given rain event, either all of the water runs off as discharge or none. In the former case C is 1 and in the latter case C is 0. C is a simple parameterisation of all the processes that occur between the rain and its appearance in the discharge. It depends on the characteristics of watershed surface (imperviousness, slope, ponding character), character and condition of the soil, rainfall intensity, proximity to water table, vegetation, land use, depressions, etc. For each watershed, C has to be determined based on the available data or information on relevant importance of all the above terms. Usually C varies between 0.1 to 0.95; an example of a typical variation of C with watershed surfaces is given by Wanielista (1990) for a return period of less than 10 years.

As discussed earlier, high flows occur fairly regularly in the rivers in the rainy season (monsoon). Most of the time a river channel has the capacity to contain this high flood, with a little spillage in the flood plain. This capacity flow (hereafter called normal or average peak flow (Q_p)) depends upon the geometry of the flow and is an intrinsic property of the watershed. It can be estimated by measurements, if available, of discharge at a given point. For example, a long term average of the discharge peaks in the rainy season, is a good approximation for Q_p. The flood condition is identified by comparing the peak discharge (Q) for a rainfall event with the Q_p (capacity or average peak flow).

4 Method implementation

A flowchart of the method is shown in Figure 4. GRASS comes with a Graphical User Interface (GUI) along with the usual command line interface. The commands mentioned here can be used in both the modes, and users are welcome to use both. The command line mode is more powerful as it can be combined with powerful GNU/Linux utilities, but is a little difficult for beginners. In this report we have used command line mode for brevity.

4.1 Flood risk analysis: Low-lying areas

First of all, it is important to identify the low-lying areas in danger of flooding. This requires a real time hydrological model with a sufficiently fine grid resolution to resolve the river channel geometry (e. g., across channel width and depth), which predicts the inundation areas based on the transient hydrological variables. In practice, setting up such models is not easy; they require extensive data including stream channel geometry. Although inundation areas are expected to vary along the river course and reach, and localisation of rainfall event, for a first approximation the areas nearest to the stream channel can be identified from SRTM DEM. At the continental and even on the regional scale, SRTM DEM is of a very fine resolution. In the case of Goa or most of the the west coast rivers, the river channel width in upstream areas is of the order of tens of metres. (The Mandovi in its upstream attains a width of around 50 metres). Thus, despite resolving the stream network accurately, even the SRTM DEM cannot resolve the cross channel geometry, its resolution is not fine enough. What is required is a DEM of still lower resolution, which is not available at the time of writing this report.

As a starting point we can identify and map low-lying areas, starting from the stream network according to slope values, which is based on an available GRASS-GIS script[1] for a modified version of the script. These are the areas most likely to be inundated first in case of a flood.

Using the SRTM DEM, a slope map can be calculated easily in GRASS. The module `r.slope.aspect` generates maps of slope and aspect. The module uses 3 × 3 neighbouring cells to calculate slope (in degrees).

In the next step, GRASS module `r.cost` is used to calculate the cumulative cost of traversing the slope map starting from the stream channel. The value of the slope for a cell is the cost of traversing the cell. Cells with low

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[1] see `http://grass.osgeo.org/wiki/Psmap_flooding_example` and Appendix F

slope, near the stream channel or in flood plain, will have lower total cost of traversing, when compared to cells farther away from the stream. This cost will increase as steeper cells are included, as will be the case with cells that are away from the floodplain. Among the many such paths possible, water flows to the path of least resistance or lowest slope cost. The module `r.cost` generates a map containing the least cumulative cost of traversing each cell from the starting cell, which in this case, are the points on the stream.

Now, the low-lying areas can be identified based on the cumulative cost map, by defining a threshold value of cost (a fraction of mean cost). In the example given for Talpona and Galjibag rivers, the threshold is chosen as one-fourth the value of mean cost for the map. The resulting area matches quite well with the observations of affected areas, containing all the locations affected during the 2 October flash floods (Figure 6). If required , this threshold can be easily changed for other watersheds. The script used in plotting Figure 6 is given in Appendix F.

4.2 Flood warning system

Identifying the flood-prone areas is important, but to provide a timely warning for impeding flood in case of an intense-rainfall event, is more crucial. A timely warning will allow decision makers and the common population to be well-prepared for the impending danger. Flood warning requires a constant watch on rainfall intensity, which is available through the AWS network. Although rainfall intensity varies spatially, for this study, data from the nearest AWS station was used.

According to the *rational method* (Equation (3.1)) for a given watershed area (A), peak discharge (Q) during a rainfall event depends on C and I:

$$Q = CIA. \tag{4.1}$$

During severe flooding, Q is much larger than Q_p (capacity or mean peak flow), as water flows out of the channel and inundates most of the flood plain. For example, for the 2 October 2009 flood event, at time of flood peak, Q was about ten times the average peak discharge Q_p.

Dividing Equation (4.1) by Q_p and defining $Q_p/A = S$ as specific discharge for the watershed and Q/Q_p as flooding index (r), Equation (4.1) can be written as

$$\begin{aligned} \frac{Q}{Q_p} &= \frac{CI}{S}, \\ \text{or} \\ CI &= rS. \end{aligned} \tag{4.2}$$

As we do not consider spatial variability in the basin (*rational method* itself is a lumped model; it considers a watershed as a whole single unit), specific discharge (S) can be assumed to be constant for a particular basin, as the area and mean peak discharge of the watershed do not change. For Talpona River its value is calculated as $4.17\,\mathrm{mm\ hr^{-1}}$ (for $A = 233\ \mathrm{km}^2$ and $Q_P = 270\ \mathrm{m^3 s^{-1}}$). The value of Q_p is provided by the Department of Water Resources, Government of Goa.

The flooding index (r) denotes the stages and severity of flood. It should be noted that normally the river will not start to flood when r is equal to one or slightly more, as Q_p is calculated from average peak flow (a river can always accommodate some more water in its channel). Severe flooding will happen when Q is much more than or in other words, in multiples of Q_p . Larger the r, more severe the flood. As the capacity of river basins varies, it is recommended that for other rivers, r and its relationship with severity should be estimated based on different levels of flooding for that particular basin.

4.2.1 Determination of I

According to the *rational method* assumption (Equation (3.1) and discussion), rainfall intensity is assumed to be constant over the time interval required to completely drain the watershed. The time interval is called T_c . Thus, it is required that the intensity should be calculated over a period equivalent to T_c . Many algorithms exist for calculating T_c, which is a function of flow distance and velocity (again a function of size of watershed, surface characteristics (friction), slope, condition or geometry of water course and volume of runoff) (Chow et al., 1988). For river basins in Goa, the time of concentration is of the order of a few hours due to large slopes and shorter river reaches. For Talpona river, it has been calculated from GRASS add-on module `r.traveltime` (`http://grass.osgeo.org/wiki/GRASS_AddOns`) and found to be of the order of 1 hour (see Figure 3). Hence, rainfall rates over a period of one hour have been used in this study.

4.2.2 Determination of C

If C is known, Equation (4.2) can be used to identify rainfall intensities that are likely to cause a flood of known severity r. In this respect, the *rational method* can be used as a simple flood warning system, where, based on the rainfall intensity a flood of particular force can be identified and the matter conveyed to the decision makers.

As discussed earlier, C depends on the watershed properties and antecedent moisture condition. The value of C can be fixed for a particular watershed based on the spatial properties (soil type, land use and hydrological condition) and temporal variability of moisture (both short-term and seasonal). As measurements of discharge are rare in Goan rivers, it is difficult to estimate C from the data. Suprit et al. (2010) have studied the hydrology of the Mandovi river, the biggest river of Goa (catchment area $\approx 45\%$ of the total area of the state). They have used a little more complicated rainfall-runoff model (called SCS-CN method: see Mishra and Singh (2003) for details). In the SCS-CN model, based on CN (some other associated parameters) rainfall is converted into runoff. Thus, C can be understood as a similar parameter to CN (Curve Number) and parameterisation developed by Suprit et al. (2010) can be utilised here.

For flash flood situations moisture variations at three different time scales are important. It is most likely that C increases or decreases as a step function of rainfall on seasonal, daily and hourly time scales.

Climatologically (based on average over many years), most of the rainfall occurs during the monsoon (June–September). The transition from the dry to the wet season occurs in (May–June). There is considerable rainfall during this onset period, but discharge in the rivers remains low. It responds to rainfall bursts only during the onset phase. Most of the rainfall during the onset phase is either lost or added to the soil moisture reservoir (which was empty during the preceding dry months) and very little of it appears in the river, hence C (0.50) is minimum (see second column under the row heading Normal in Table 2).

After some time, following the onset of the monsoon, the soils become saturated with moisture. In the peak-monsoon rainfall bursts, most of the rainfall contributes to the river discharge. Whatever rainfall is received on the surface just runs off, and there is practically no absorption. This makes C (0.90) maximum (see third column under the row heading Normal in Table 2).

After the peak monsoon (from September–October), rainfall decreases and rain events also decrease. By this time the soil moisture reservoir is completely filled, and all the water bodies in the watershed including groundwater reservoirs and ponds are filled with water. But, since rains are infrequent, these reservoirs start drying. This makes the value of C (0.80), a value between the values in peak-monsoon and onset-monsoon (see fourth column under the row heading Normal in Table 2). The seasonal variation of C is considered a base value, and it includes the physical characteristics (soil type and land cover) averaged over the whole basin (as in Suprit et al. (2010)).

Next, there is variability within each season. For example, in peak monsoon months, there are active and break periods resulting in wet or dry spells. In wet spells, more rainfall runs off as compared to dry spells and vice versa. Hence, C also varies according to the wet or dry spells; these dry and wet spells are identified based on the rainfall of the previous five days. If rainfall during previous five days is greater than a threshold value (250 mm), conditions are identified as wet; and if less than a threshold value (100 mm), conditions are identified as dry. These threshold values are chosen based on simulations of Suprit et al. (2010), using basin scale constant parameters. Suprit et al. (2010) have also used different thresholds for different seasons to improve the discharge simulation. Since our objective is to identify the flood peaks, we have used the seasonal average values of the thresholds.

Apart from the daily variation in runoff generation processes, variations are observed within a day also. Over a day, rainfall may not occur continuously, but in bursts. A substantial rain burst in a day, whether it occurs in dry or wet spells, can make the soil wet enough to allow more runoff generation, and will increase the value of C for that spell. Even, a dry period (no rainfall burst), will make the conditions less favourable for runoff generation. Since our interest is in estimating flood flows (magnitude much larger than average peak flow) to give warning, C is not reduced further. Rainfall bursts are identified by average rainfall rate in the last five hours. If average rainfall rate is higher than a threshold value, C has to be increased from its current value to account for the rain burst. The threshold chosen for Canacona is 15 mm hr^{-1}, this threshold is chosen by a subjective method. Although it works for the event of 2 October 2009, more analysis of hourly rainfall is required.

4.3 Flood warning

The flood warning algorithm is tested for the flood of 2 October 2009. The rainfall data from the nearest AWS at Canacona is used. Using the rainfall intensity from AWS, total rainfall in the last five days and average intensity in the last five hours are calculated (see Table 3). Now based on Table 3, at every hour the value of C is fixed.

At any point on the river, based on Equation (4.2), a curve (a rectangular hyperbola for variables C (X-axis) and I (Y-axis)) can be drawn for different values of r. This flood warning plot, is colour coded for ease of operation, emphasizing the different stages of severity and possible course of action, see Figure 8 for Talpona river. Once C is estimated, I and C values (e. g., see Table 3) can be used to locate and plot a point on the flood warning map (Figure 8. Based on where the point lies, appropriate warnings or actions can be issued. For example, $r > 10$ is a severe flood condition and warning should be given prior to the development of this condition (e.g. $r > 5$).

We will retrace the event of 2 October 2009 and will check if the method gives a timely warning. We start our watch-keeping from 00:30 IST. At the start of the day, C has the value of 0.8, the base value for the season, since the five-day rainfall is less than 250 mm (and greater than 100 mm) (Table 3). From 0:30 IST to 03:30 IST, except for a single burst at 2:30 IST, rainfall is scanty. At 03:30 IST $C = 3.0\,\text{mm}$ and $I = 0.8$, thus the point lies in the green zone (just watch-keeping). At 4:30 IST, there is a huge burst of rainfall, which, for the same value of C (0.8), makes the point lie in the severe flood category, because of large I ($I = 58.0$ mm hr^{-1}). Although the 4:30 IST point lies in the severe flood category, a warning should not be issued because rainfall may not be sustained beyond an hour's burst, which was found to be the case. But in any case, large bursts like these, should alert the watch-keepers. After this event and the 2:30 event, the soil becomes wet and conditions turn into wet burst as the average rainfall intensity is now more than the threshold value. Thus, C increases to 0.9, for the next hour. Rainfall becomes steady after 4:30 IST, and on the flood warning map, points lie in the watch keeping zone. Steady rainfall adds to the soil moisture reservoir, making it saturated at 7:30 IST, hence C (0.95) is maximum (wet burst in wet spell). At 10:30 IST, rainfall again picks up ($I = 32$ mm hr^{-1}) and the point lies in the action zone. Value of C has to decrease from 0.95 to 0.90 as the 04:30 burst is no longer in the range of calculating the rain rate of the last five hours. The threshold is just below 15 mm hr^{-1}); this looks strange as the soil is still expected to be saturated. The problem is due to the definition of threshold. After 10:30 IST heavy rainfall continues, and these peaks make the C again maximum. Hence, at 10:30 IST, precautionary measures and drills should start. At 11:30 ($I = 32$ mm hr^{-1}) the peak continues, and the point lies in the action or warning zone. The watch-keeper should be ready to declare the warning. As peak rainfall continues, with soil already saturated ($C = 0.95$), by 12:00 IST warning should be disseminated.

This warning is useful, as it gives a lead time of around an hour. Due to continuous heavy rainfall, points from 14:30 IST to 15:30 IST lie in the severe flood category. This compares well with the flooding description given in CFFSC (2009), where severe flooding occurred after noon. After 04:30 IST, rainfall reduces to ease the flooding. One should be careful about the occurrence of isolated peaks (like 04:30 IST). Isolated events such as these should increase the alertness of watch-keepers. They may not cause flash floods (since rain rate has to be sustained over few hours), but they may indicate a possibility of flash floods, if heavy rainfall continues.

5 Conclusions

As seen from the results, the method is able to assess the flood risk for the Talpona river flood event of 2 October 2009. Based on the slope values (e. g., Figure 6 for Talpona and Galjibag rivers), a map of flood-prone low-lying areas (areas can be prepared for identifying the most vulnerable areas.

Applying the rational method will give the peak discharge for selected points on the river. A user who has some prior knowledge of mean flow of the stream (Water Resources Department of Goa estimates mean discharge of most rivers of Goa), can compare the peak discharge in the case of an intense-rainfall event with the mean discharge to ascertain the flood risk. Then the user can prepare flood warning maps (e. g., Figure 8 for Talpona river) to assess the flood risk based on rainfall intensity and runoff coefficient.

Thus, the method can be used in practice and is very simple to implement. The main strength of the method is that it uses freely available tools and data. Users are free to add local details and modify the method. Only an elementary knowledge of GIS and hydrology is required.

One of the drawbacks is the parameter estimation in the *rational method*. The method does not prescribe any specific methodology to calculate parameters T_c and C: it requires observational data, which is not readily available. So, parameters must be specified based on some prior knowledge of the river flow regime and objective in hand. Hydrologists criticise the over-simplified approach of *rational method*, but also recognise its importance as a means of preliminary analysis. Hence, it is still one of the most widely used methods (Chow et al., 1988; Beven, 2001). Another problem with this method is the estimation of rainfall intensities; not all the places in Goa are covered by AWS, and rainfall varies a lot with place. The problem of estimation of rainfall is addressed in the third report of CFFSC, where installation of more AWS is proposed.

It is hoped that the method discussed here will stimulate a positive reaction among students. We also hope that their participation will result in improvement of existing methods, by including more realistic hydrological routing models and methods.

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After the flash floods of 2 October 2009, we conducted field surveys of the flood affected areas. We are thankful to Mr. T. P. Simon and Mr. D. Sundar for their help in logistics. We also thank Mr. Sarvesh Chandra who accompanied us on the field trips. The field surveys were possible only due to the untiring and round-the-clock help offered by Shri Kavindra Phaldesai, S. S. Angle Higher Secondary School, Mashem, Canacona. We would also like to thank all the people of Canacona Taluka with whom we interacted; even in their suffering, they welcomed us and patiently answered our questions.

Appendix A SRTM DEM

Shuttle Radar Topography Mission Digital Elevation Model SRTM DEM is a digital representation of earth's topography. In a DEM, the surface is divided into a grid of rectangular cells (called grid cells or pixels). The average height of land surface, determined by remote sensing techniques, covering each pixel is stored in digital format. The pixel size of a SRTM DEM is 3 arc-second (~ 90 meters at equator) and the average height of the pixel is stored at the centre of the pixel. The SRTM DEM is fairly accurate, the absolute vertical error for Eurasia is 6.2 m at 90% confidence level (better than 9% for global) (NASA SRTM). SRTM DEM was produced using data obtained from the NASA space shuttle Endevour's flight in February 2000. The shuttle carried two radars (Synthetic Aperture Radar), which collected the data (inteferometric SAR) of the target location for 11 days (159 orbits) on a 1-arcsecond resolution (Farr et al., 2007). The SRTM data is made freely available (`http://www2.jpl.nasa.gov/srtm/`) by NASA on 1-arc second resolution for United States of America and resampled 3-arc second resolution for global areas in the form of 1 degree tiles. A drawback of the SRTM data is that it contains data-holes (no-data values). The data-holes were caused primarily for two reasons: first, due to the steep slopes facing away or towards the radar (directing radar signals away from the radar or towards the radar) biggest errors in Himalaya and second, smooth surfaces such as water bodies (lakes or rivers) or sand (biggest errors in Sahara) which scatter little energy towards the radar.

The SRTM DEM is downloaded from the CGIAR-CSI (`http://srtm.csi.cgiar.org`). The CGIAR-CSI uses post-processing and interpolation methods to fill the data-holes (CGIAR SRTM).The resultant DEM is a little coarser than the original SRTM DEM, due to interpolation. The SRTM data at CGIAR-CSI is available in the form of 5° by 5° tiles, which can be downloaded from their graphically searchable web page.

Although, SRTM DEM downloaded from CGIAR-CSI is a filled DEM (data-holes are filled), it is observed that for the west coast of India, the filled SRTM DEM has negative values (different from the no-data value of -32767).

These negative values are obviously wrong and arise from the inaccurate sea-land masking or due to interpolation (filling) algorithm of CGIAR-CSI. For hydrological analysis, DEM should be free of sinks and other artifacts (plateaus,dams) and every cell in the DEM should be connected to the outlet point. In other words, DEM should be hydrologically correct. Filling the artificial sinks, is most crucial. Sinks block the flow instead of allowing it to flow out. They are also the cause of the segmented or incomplete stream networks. One way to remove the sinks and other artifacts is to obtain the actual stream network map from the toposheets and edit the cells (manually or using algorithm) accordingly. But this process is time consuming (almost impossible for SRTM for basins of reasonable sizes; for a basin of size 2000 km^2 , total number of cells $\approx 2.4 \times 10^6$) and stream network data may not be readily available.

We used a software project, called `TerraFlow`, computations on massive grids, (website `http://www.cs.duke.edu/geo*/terraflow/`) to derive a hydrologically correct version of SRTM DEM (Toma et al., 2003; Arge et al., 2000). The project is designed using efficient algorithms for flow computation on massive numbers of grid-cells containing terrain, such as SRTM DEM. `TerraFlow` computes the flow routing (path when a volume of water is poured on the terrain) and flow accumulation (amount of water flowing through the terrain) from a given DEM. It is much faster (2 to 1000 times) than the other algorithms and has been used on massive datasets, up to 10^9 (1 billion) in size (Toma et al., 2003). It uses a flooding algorithm to fill the sinks in a DEM. The algorithm is explained in detail in Arge et al. (2001).

`TerraFlow` is implemented in GRASS GIS as module `r.terraflow` (and module `r.terraflow.short`[2] for DEMs containing elevation as an integer). This module is used for obtaining the hydrologically correct DEM.

```
r.terraflow.short -s elev=srtm_west_coast \
 filled=srtm_west_coast_filled
```

---

[2] For more detailed information about GRASS commands used, see the online GRASS documentation project (`http://grass.itc.it/gdp`) (updated information), module *g.manual* (html manual), *man* command and putting *help* after the command.

Appendix B Data management

A feature of GRASS GIS is the concept of location and mapset for managing the projects. A location is a geographic extent of interest which a user decides upon in a particular coordinate system (e. g., latitude-longitude or UTM). The data is saved in the subdirectories of location called mapsets. In the mapsets, a user can organize the data as he wishes (based on a theme, region or project). The geographical extent of the mapset is the same (or it can be smaller) as the parent location. GRASS creates a default mapset called PERMANENT. In this PERMANENT mapset, basic and essential (like map projection) information and some base data sets are kept, where the *write* access is only available to the user who creates the location. In a large project or networked environment, if there are multiple users , they can create their own mapsets, which they can select and modify for subsequent use. However, data in all mapsets for a given location can be read by anyone. This structure provides flexibility where on a big project, multiple users can work simultaneously.

The users will be provided a default location named (*goa_flood*), with two mapsets (*PERMANENT* and *user*) already created.

The `goa_flood` location contains the SRTM DEM (a raster image `srtm_west_coast_filled`) in the `PERMANENT` mapsets, available to the user. A suit of secondary data layers (digitized vector maps of Mandovi, Zuari, Talpona and Galjibag Rivers; Goa state boundary and some key locations) are also provided to the user.

Appendix C Steps for calculating the watershed area

Here steps used in watershed analysis are explained in detail. We have used command line implementation of the procedure:

1. Starting GRASS

Start terminal (e. g., `konsole`) and enter (Figure 9)

```
$grass64 -wxpython
```

2. Selecting project location and mapset

   After start, GRASS will open both the modes (command line and GUI) (Figure 10). The user will have the option to continue working in the same mapset or create a new mapset. In the latter case he can copy the DEM provided in its own mapset.

3. Setting the geographical region of interest

   A user has an option to set the geographic region in which he is interested. The user has an option to set multiple regions, but only one region definition will be valid at any given time. The region can be selected either by giving the longitude and latitude of the four corners or can be selected through zooming or panning on a displayed map.

   Here an example is given to select the region by using zoom application of the GRASS GIS.

   First of all we make sure the region is the default (same as the DEM supplied) (Figure 11).

   ```
   $g.region rast=srtm_west_coast_filled
   $g.region -p
   ```

   Open a GRASS monitor and visualize the DEM (Figure 12).

   ```
   $d.mon start=x0
   $d.rast map=srtm_west_coast_filled
   ```

4. Mask map calculation

   This `MASK` map is used to mask the areas not included in analysis. GRASS watershed analysis module requires `MASK` map to be predefined.

Grid cells having elevation greater than 0 are given a value of 1 and the rest of the map is given null value.

```
$r.mapcalc "mask_map = if (srtm_west_coast_filled > 0, \
 1, null())"
```

5. Save as default mask

   The mask map is copied to the default mask name `MASK`. From now on all the calculations are done only for the masked areas. This map can also be displayed (Figure 13).

   ```
   $g.copy  mask_map, MASK
   $d.rast mask_map
   ```

6. Zooming into the project location

   Zoom into a specific area using `d.zoom` command after re-plotting the SRTM DEM, in this case region around Talpona river (Figure 14).

   ```
   $d.rast map=srtm_west_coast_filled
   $d.zoom
   ```

   Zooming is done using mouse buttons: click left to select the first corner of the area. Scroll and click middle button to select the second corner to zoom to the area. After zooming, click the middle button to unzoom the area and, once done, user can quit the program by right clicking.

   Now the region is set to the zoomed area. User can save this region definition using `g.region` command to be used in subsequent sessions (Figure 15).

   ```
   $g.region save=talpona_region
   ```

   Further a user can save DEM as a subset of much larger DEM for the whole area (Figure 16).

```
$r.mapcalc "srtm_talpon_dem = srtm_west_coast_filled"
$d.rast map=srtm_talpon_dem
```

7. Watershed basin analysis program

   The watershed analysis is the most important step in order to determine the basin geometry and stream network. The `r.watershed` module allows the user to determine the basin geometry (basin map, stream map, drainage map, etc.) from a given DEM (Figure 17).

   ```
   $r.watershed --o elevation=srtm_talpon_dem threshold=1000 \
   drainage=drainage_talpon stream=stream_talpon \
   visual=visual_talpon basin=basin_talpon
   ```

   The input parameter `threshold` is an integer value which denotes the minimum size of watershed basin in cells. Thus a lower value of this parameter generates a more detailed stream network (with many small watersheds associated with streams and substreams). A large value of this parameter gives a less detailed map of the streams, as only one stream per watershed is presented. The large value of the parameter gives overall basin structure of the river system (small watershed will be clubbed together to form a basin). The value of this parameter is estimated based on the above criteria and keeping in mind the river basin geometry (from toposheets or other maps).

8. Visual rendering of output maps

   The output maps, especially the basin and stream maps, should be checked by visual inspection. If required, user is welcome to change the `threshold` parameter and above steps can be repeated (see Figures 18 and 19).

```
$d.erase
$d.rast map=basin_talpon
$d.erase
$d.rast stream_talpon
```

9. Choosing a point on the stream over which watershed area will be estimated.

   In order to calculate the watershed area for the river the user has to select a point on the river using the stream map from the above step (re-plotting Figure 19).

   ```
   $d.erase  $d.rast map=stream_talpon
   ```

   The GRASS GIS raster map query command `r.what.rast` is used to query the latitude and longitude of the point on the river. The right mouse click will give the location. The point should exactly lie on the stream, and `d.zoom` can be used to zoom the map.

   ```
   $d.what.rast
   ```

   The right mouse click will give the location (Figure 20, user must choose a *non-null* value). The point should be exactly on the stream, and `d.zoom` can be used to zoom into the map. The location is converted into decimal degrees.

10. Watershed creation

    The `r.water.outlet` module is used to create the watershed over the selected point on the stream. The module requires the drainage map and location (easting (longitude) and northing (latitude)) generated from above step. The output is the raster watershed (basin) map over the selected point.

```
$r.water.outlet drainage=drainage_talpon
  basin=watershed_talpona \
  easting=74.0502798  northing=14.9884136 --o
```

It is always a good idea to check the output (Figure 21).

```
$d.rast basin_talpona
```

11. Converting watershed map (a raster map) to watershed divide (a vector map)

    To get the watershed divide (basin perimeter) of the watershed,it is better to convert the raster basin map to vector (Figure 22).

    ```
    $r.to.vect -s input=watershed_talpona  \
    output=basin_talpona_74_050_14_988_vect feature=area
    ```

    Again it is advisable to check the output. Note that to visualise the vector map, we use `d.what.vect` command (Figure 23).

    ```
    $d.erase
    $d.vect basin_talpona_74_74_050_14_988_vect
    ```

12. Area of the watershed

    After displaying the output vector map, it can be queried to get the area of the watershed. The command `d.what.vect` is similar to the earlier discussed `d.what.rast` and a mouse click on any where in the watershed will give the area in different units (Figure 24).

    ```
    $d.what.vect -x
    ```

13. Using rational method to calculate peak discharge Q during a rainfall event

Using the rational method (Equation (3.1)), the peak discharge for a particular rainfall intensity can be calculated after estimating the other parameters. User can perform this operation on his own choice of programs such as a spreadsheet software or a calculator. (Figure 25).

Appendix D Script for calculating watershed area

The steps explained in Appendix C are automated in the interactive script given below. Once the user is familiar with GRASS commands, the script can be executed to obtain the watershed area at any desired point.

```
#!/bin/bash

#%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%#
#                                                               #
# PROGRAM DESCRIPTION:-                                         #
# The bellow Bash script is a set of grass commands          #
# for determining the basin area            #
# of a river.                                                   #
#                                                               #
# REQUIREMENTS:-                                                #
# GIS-GRASS                                                     #
# GRASS Database                                                #
# grass_readme.txt                                              #
#                                                               #
# To run the script open GRASS command line and move to the   #
# location where the bash      #
# file is saved and check if the script is in executable        #
# mode if not then              #
# ($chmod +x grass_cmds_bash.sh).Then run the script            #
# ($./grass_cmds_bash.sh)            #
#                                                               #
#%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%#

#Open Readme file for User Guide.

gedit grass_readme.txt &
```

```
# Define the region under calculation by setting it to default
# region (i.e., the DEM used)

g.region rast=srtm_goa_filled_new


# Remove the previous masks which had been used for earlier
# calculation

g.remove MASK


# Use mapcalc function to create a mask from the DEM of Goa,  by
# assigning all the grid cells having elevation greater than 0 by
# an elevation of 1 and the rest of the map is given a null value.
# This is how we can mask the areas which are not included in the
# analysis.

r.mapcalc "goa_mask_creating=if(srtm_goa_filled_new>0,1,null())"


# The mask map created is copied to the default mask name 'MASK'.
# Calculations from now on will be done only on the required
# areas.

g.copy goa_mask_creating,MASK


# Open the graphics monitor named 'x0' to visualize the MASK map.

d.mon start=x0


# Erase the selected monitor 'x0'

d.erase


# Display the raster MASK map on graphics monitor 'x0'
```

```
d.rast MASK


# Open the graphics monitor named x1 to visualize DEM map

d.mon start=x1


# Erase the selected monitor x1

d.erase


# Display the DEM (SRTM raster data map) map on graphics monitor
# x1

d.rast srtm_goa_filled_new


# Enter the Threshold value which is an integer value, which
# denotes the minimum size of watershed basin in cells,lower value
# will generate a more detailed stream network and larger value of
# this parameter gives a less detailed map of streams.

echo "enter the Threshold value:" read thresh


# To generate the watershed basin for hydrological calculation The
# watershed analysis is the most important step in order to
# determine the basin geometry and stream network.  The
# r.watershed module allows the user to derive the basin geometry
# (basin map, stream map, drainage map, visual map etc.) from a
# given DEM.

r.watershed --o elevation=srtm_goa_filled_new threshold=$thresh \
drainage=drain_goa stream=stream_goa visual=visual_goa
basin=basin_goa


# Open the graphics monitor named x2 to visualize stream map
```

```
d.mon start=x2


# Erase the selected monitor x2

d.erase


# Display the stream map generated from watershed calculation on
# graphics monitor x2

d.rast stream_goa


# Zoom to take closer view of the river under study.  1.) Use the
# left mouse click to select the region to zoom and use middle
# click to zoom.  2.) Use only middle click on the map to unzoom.
# 3.) Use right click to exit zoom.

d.zoom


echo -e "Use Left Mouse Click on the river to get the Latitude and
Longitude\n"


# d.what.rast is used to get the lat/long of the point on the
# river which is used to calculate the basin from the selected
# point to the upstream can be queried by left mouse click of the
# point on the river, see that the point should lie exactly on the
# stream.The Latitude and The longitude will be displayed on the
# GRASS command line.  Use right mouse click to exit the command.


d.what.rast>grass_canacona_lat_lon.txt

#The output of this command is taken into a text file

#Intake of Latitude & Longitude variables from the Terminal#
```

```
#Read last two lines of the file

line=‘tail -2 grass_canacona_lat_lon.txt‘

#declare your array declare -a var

#split your line using tr

var=(‘echo $line | tr ’ ’ ’ ’‘)

la=‘echo ${var[1]}‘ lo=‘echo ${var[0]}‘

#Delete the temporary text file

rm -f grass_canacona_lat_lon.txt

#~~~~~~~~~END~~~~~~~~~~~~~~~~~~~~~~~~~~~#


# The d.zoom command changes the default region
# co-ordinates to zoomed region co-ordinates.
# Revert back to the default region

g.region rast=srtm_goa_filled_new


# Give a basin name for easy recognition (e.g.
# Mandovi_Basin).

echo "PLease enter the name of the river basin:" read basin_name


# r.water.outlet module is used to create the watershed over the
# selected point on the stream.The module requires the drainage
# map and location (easting(longitude) and northing (latitude) in
# decimal) generated from the above steps.  The output is the
# raster watershed(basin) map over the selected point.

r.water.outlet drainage=drain_goa basin=$basin_name easting=$lo \
northing=$la --o
```

```
# Open the graphics monitor named ’x3’ to visualize the
# watershed(basin) map.

d.mon start=x3


# Erase The selected monitor ’x3’

d.erase


# Display the raster watershed(basin) map generated from the above
# watershed calculation on the graphics monitor ’x3’

d.rast $basin_name


# Zoom to take closer view of the basin under study.  1.) Use the
# left mouse click to select the region to zoom and use middle
# click to zoom.  2.) Use only middle click on the map to unzoom.
# 3.) Use right click to exit zoom.

d.zoom


#  Save the basin file at the point where it was
# calculated; for easy recognition  latitude and
# longitude are added to the file name  (we replace the decimal
# point to "_" (e.g., 12.234 to 12_234)

lon=‘echo ${lo/./_}‘ lat=‘echo ${la/./_}‘

# Converting the raster basin map to vector in order to get the
# basin perimeter.  The output watershed divide (vector map) is
# saved, filename will include both basin name and the location (latitude and
# longitude) of the point on the stream.

r.to.vect -s input=$basin_name output=$basin_name\_$lon\_$lat \
feature=area --o
```

```
# open the graphics monitor named x4 to visualize the vector map.

d.mon start=x4


# Erase the selected monitor x4

d.erase


# Display the vector map which shows the basin perimeter on the
# graphics monitor x4

d.vect $basin_name\_$lon\_$lat


# d.what.vect -x is used to get the Area of the displayed vector
# map on graphics monitor 'x4' one can query it by using left mouse
# click any where inside the basin perimeter to get the Basin Area
# in different units (Sq. Meters, Hectares, Acres, Sq. Miles) on the
# GRASS command line.  Use right mouse click to exit the command.

d.what.vect -x


# Here we resize it in order to run the script multiple number of
# times without closing GRASS which otherwise would cause
# visualization problem while displaying in the same graphic
# monitors(ie x0,x1,x2,x3,x4) due to zooming.

g.region rast=srtm_goa_filled_new

#~~~~~~~~~~~~~~~~~~~~~THE END~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~#
```

Appendix E Script for making shaded basin map

The following script can be executed in the GRASS GIS to obtain the basin map (Figure 2).

```
#!/bin/bash

#Run from GRASS GIS
#Script modified from GRASS man-pages
#

#
#r.watershed elev=srtm_west_coast_filled accum=$MAP threshold=100
#
#r.watershed elev=srtm_west_coast_filled basin=$BASIN thresh=100000

#######################
DEM=srtm_west_coast_filled

ACMMAP=accum_goa1f_100n
BASIN=basin_goa1f_100000n

RCOURSE=rwater_course
#######################

#Set a color table for the accumulation map

eval ‘r.univar -g "$ACMMAP"‘
stddev_x_2=‘echo $stddev | awk ’{print $1 * 2}’‘
stddev_div_2=‘echo $stddev | awk ’{print $1 / 2}’‘

r.colors $ACMMAP col=rules << EOF
    0% red
    -$stddev_x_2 red
    -$stddev yellow
    -$stddev_div_2 cyan
    -$mean_of_abs blue
    0 white
    $mean_of_abs blue
```

```
    $stddev_div_2 cyan
    $stddev yellow
    $stddev_x_2 red
    100% red
EOF


#Create the mask is it is not already defined
#r.mapcalc 'MASK = if(!isnull(goa_full_filled_terraflow2))'
```

Appendix F Script for making map of low-lying areas

The following script can be executed in GRASS to obtain low-lying flood-prone area map (Figure 6).

```
#!/bin/bash

#Run in Grass
#Modified from the GRASS user script
#Original script available
#at (http://grass.osgeo.org/wiki/Psmap_flooding_example)

############
# Input maps and strings
############
DEM=srtm_west_coast_filled

OUT=talpona_risk_area.ps
BASIN=basin_goa1f_5000n
RCOURSE=rwater_course

FLOOD_BASINS=220,222,224,226
TIMESTAMP=`date`
FLOOD_PRONE_LOC=places_previous_flood
############
```

```
#remove old maps
g.remove rast="$DEM"_cost_from_rivers,flood.zones vect=flood_zones


########
# Next we designate the low lying areas.
#  Ideally this would come from a real-time hydrologic model.
########


# Create danger polygons for each catchment
# (home-brew example of predictor for at-risk low-lying areas)

r.cost -k in="$DEM" out="$DEM"_cost_from_rivers start_rast="$RCOURSE"
r.colors "$DEM"_cost_from_rivers col=bcyr -e

#  Choose a threshold value. This could be based on hydrologic model output
#  for now just set for lower half of slope-costs in the map
eval ‘r.univar -g "$DEM"_cost_from_rivers‘
r.mapcalc "flood.zones = if("$DEM"_cost_from_rivers < ($mean/4), \
     "$BASIN", null() )"

# convert to vector areas
r.to.vect -s in=flood.zones out=flood_zones feature=area
v.db.dropcol map=flood_zones column=label
v.db.renamecol map=flood_zones column=value,catchment

########## Next we set the dynamic data, either automatically from model
# output or though interactive selection & highlight of areas (e.g. a script
# using the HTMLMAP driver, ’d.what.vect -xft’, or d.ask) ##########
#
# Here we say catchment #6 and #12 (FLOOD_BASINS=220,222,224,226
# ) are at risk.


#The rest is a static template. Here we pass the command through the shell
#but the input file could be written to a file (taking care to process
#environment variables) and then passed to ps.map’s input option.

# convert catchment list to SQL query
FLOOD_BASIN_SQL=‘echo $FLOOD_BASINS | \
```

```
  sed -e ’s/^/catchment = /’ -e ’s/,/ OR catchment = /g’‘

# generate Postscript image
ps.map out="$OUT" << EOF
raster  $DEM
# example of dashed lines
#vlines roads
#  style 000011
#  where label ~ ’highway’
#  width 0.25
#  label Highways
#  end
vlines $RCOURSE
  color grey
  label Water courses
  end

vpoints $FLOOD_PRONE_LOC
type point
color black
fcolor black
symbol basic/diamond
size 10
label Places affected by 2 October 2009 flood
end

#vareas  $BASIN
vareas flood_zones
#change to "flood_zones" vector map for lowlying areas instead of
#  entire catchment
where $FLOOD_BASIN_SQL
  color red
  fcolor red
  width 2
  pat $GISBASE/etc/paint/patterns/polka_dot.eps
  label Catchement area subject to flood risk
  end
vlegend
  end
text 100% -3% Warning issued $TIMESTAMP
  font Helvetica-BoldOblique
```

```
  fontsize 12
  ref right
  end

#River specific text label

text  45% 70% Talpona River
  font Helvetica-BoldOblique
  fontsize 12
  ref right
  end

text  75% 15%  Galjibag River
  font Helvetica-BoldOblique
  fontsize 12
  ref right
end

end
EOF
```

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River	**Location**	**Latitude** (°N)	**Longitude** (°E)	**Area** (in km^2)
Terekhol	Aronda	15.72698	73.723723	603.57
Chapora	Chapora	15.65461	73.82104	822.69
Valvanti	Sanquelim	15.55468	73.99028	112.70
Mhadei	Valpoi	15.51537	74.13645	447.03
Mandovi	Panaji	15.50273	73.82641	1963.55
Zuari	Cortalim	15.41470	73.90979	917.27
Sal	Mobor	15.16012	73.95279	241.25
Saleri	Saleri	15.05297	73.98109	50.88
Talpona	Piplibag	14.98948	74.05644	184.08
Galjibag	Mugdal	14.96129	74.04947	71.06

Table 1: Results of watershed analysis of all the main rivers of Goa at a location mentioned in the table (Figure 5). (Location is name of nearest place from the stream.) The watershed area calculated here can be used along with the AWS rainfall data (in Equation (3.1)) to calculate the peak discharge at the location mentioned.

Variation of C	**Temporal Scales**		
	Onset Monsoon May–June	**Peak Monsoon July–August**	**End Monsoon September–October**
		Seasonal	
Normal (Base)	0.50	0.90	0.80
		Daily	
Dry spells	0.30	0.79	0.63
Wet spells	0.70	0.90	0.95
		Hourly	
Wet burst in dry spells	0.50 (0.30)	0.90 (0.79)	0.80 (0.63)
Wet burst in wet spells	0.84 (0.70)	0.98 (0.95)	0.95 (0.90)

Table 2: Dependence of C (in %) based on soil moisture conditions. Thus, C, varies with the seasons, minimum in Pre (or Onset) Monsoon and maximum in Peak Monsoon. As there are breaks and active periods of rainfall in each of the seasons, soil gets drier or wetter accordingly, changing the C. The dry spells in a season are identified as times when rainfall of the last five days is less than 100 mm; and wet spells when rainfall of the last five days is more than 250 mm. This parameterisation is similar to that done by Suprit et al. (2010), C is assumed to be similar to Curve Number. Finally, C also varies during a day, as a burst of rainfall may not be absorbed quickly by the soil. On the hourly scale, although soil gets wetter pretty fast, it does not dry that fast. And since, our interest is in peak flood flows, in the hourly scales, C is not lowered below its normal base value. So when rainfall rate of the last five hours rainfall rate is greater than a threshold rate (15 mm hr^{-1}), C is increased from the value at daily time scale (e. g., from 0.90 to 0.95; see last two rows in table).

Time	**Rainfall rate** (mm hr^{-1})	**last 5-day rain** (mm)	**last 5-hour rate** (mm hr^{-1})	C
00:30 IST	1.0	142.0	0.4	0.8
01:30 IST	3.0	145.0	0.6	0.8
02:30 IST	19.0	164.0	1.0	0.8
03:30 IST	3.0	167.0	4.6	0.8
04:30 IST	58.0	225.0	5.2	0.8
05:30 IST	11.5	236.5	16.8	0.9
06:30 IST	11.5	248.0	18.9	0.9
07:30 IST	12.0	260.0	20.6	0.95
08:30 IST	11.0	271.0	19.2	0.95
09:30 IST	14.0	285.0	20.8	0.95
10:30 IST	32.0	317.0	12.0	0.9
11:30 IST	32.0	349.0	16.1	0.95
12:30 IST	32.0	381.0	20.2	0.95
13:30 IST	32.0	413.0	24.2	0.95
14:30 IST	47.0	460.0	28.4	0.95
15:30 IST	48.0	508.0	35.0	0.95
16:30 IST	48.0	556.0	38.2	0.95
17:30 IST	5.0	561.0	41.4	0.95
18:30 IST	5.0	566.0	36	0.95
19:30 IST	1.0	567.0	30.6	0.95
20:30 IST	1.0	568.0	21.4	0.95
21:30 IST	2.0	570.0	12.0	0.9
22:30 IST	2.0	572.0	2.8	0.9
23:30 IST	6.0	578.0	2.2	0.9

Table 3: Estimation of C based on antecedent rainfall. First column (C1) is time in IST, Canacona AWS rainfall rate is given in second column (C2). In C3, total rainfall in last five days (in mm) is given; and in C4, average rainfall rate in the last five hours (in mm hr^{-1}). In the last column, C5, estimated values of C is given.

Default region settings	
Projection	longitude-latitude
Datum	WGS84
North	16° N
South	14° N
West	73° E
East	75° E
Resolution	3 arc-seconds (0.00083333)
Cells	2400 × 2400 (5760000 cells)

Table 4: Default region setting for *goa_flood* location. User can select any subset of the default region, using `g.region` command.

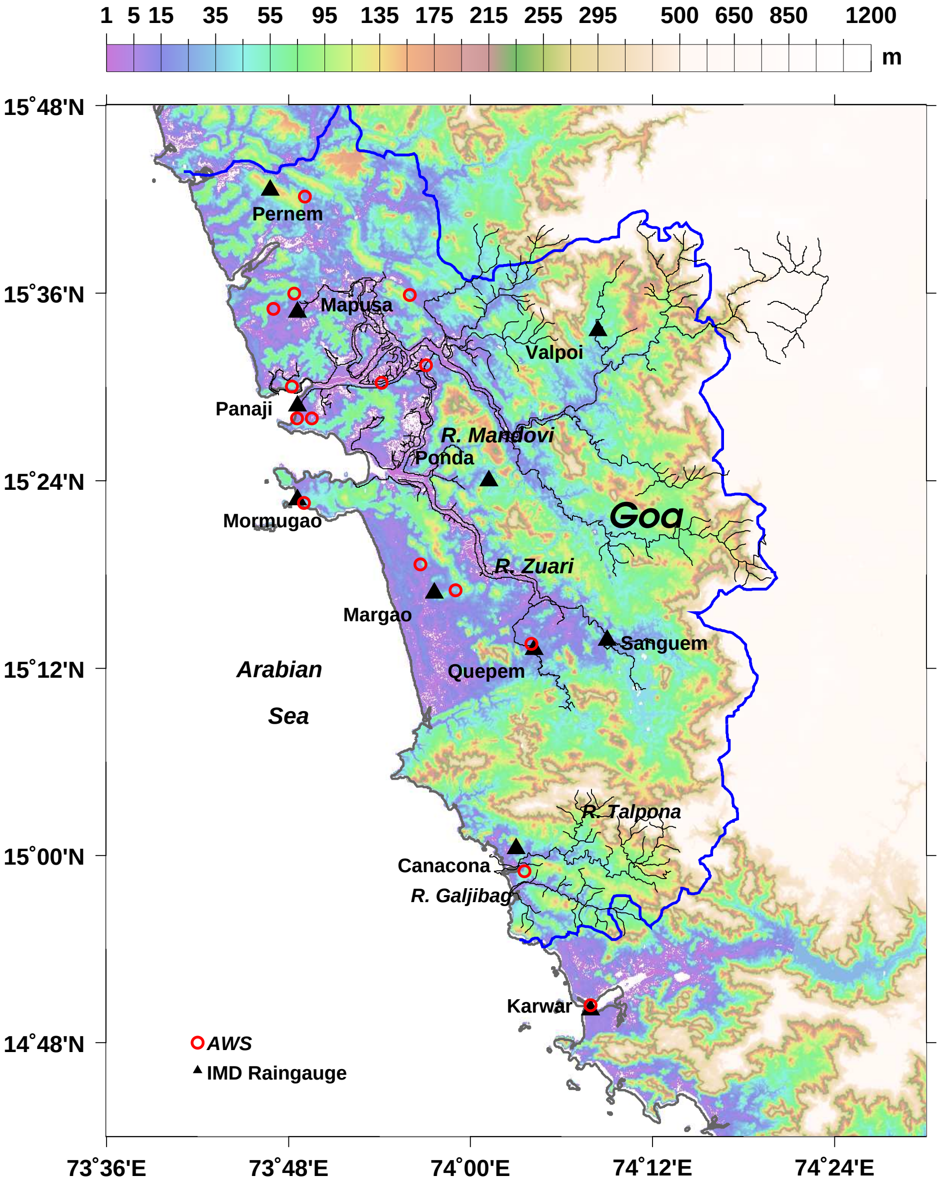


Figure 1: The topographic map (topography from SRTM DEM) of Goa and its surroundings. The colour scale at the top of the figure gives topography (elevation in m). The blue line marks the border of Goa. Locations at which rainfall data are available are also shown on the map (black triangles are India Meteorological Department rain-gauge stations and red circles are Indian Space Research Organisation's Automatic Weather Stations (AWSs)).

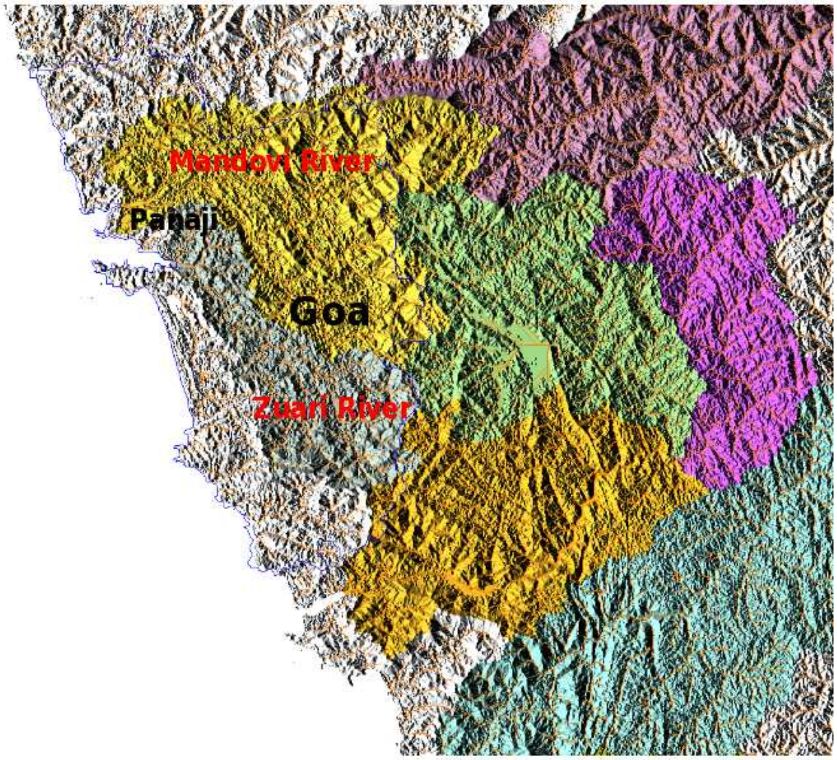


Figure 2: Module *r.terraflow* of GRASS GIS is used to generate the hydrologically corrected SRTM DEM. The river basins (Mandovi and Zuari basins are marked) are plotted in different colours along with stream network (in orange). The river basins are draped over the shaded relief generated from SRTM DEM. A script which was used to plot this map is included in Appendix D, which can be modified easily to plot such maps for any region.

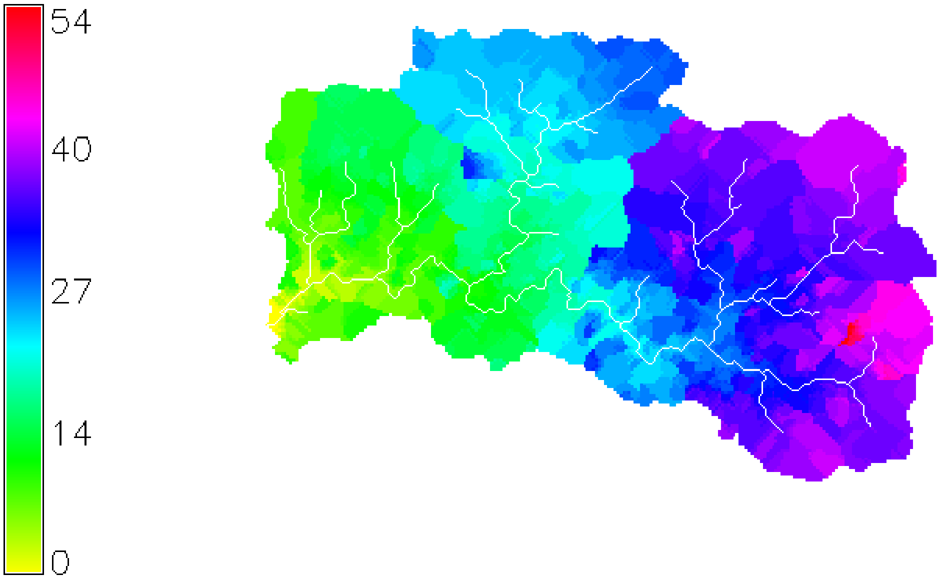


Figure 3: Module *r.traveltime*, a user-contributed module of GRASS, is used to estimate travel time (in minutes) for Talpona River basin. Estimation of travel time is important for application of *rational method*. Travel time depends on the watershed surface characteristics (slope, roughness, channel geometry, etc.) and specific discharge. Many of these parameters are not available for Goan rivers. The parameters used are based on approximation along with the default values of parameters provided with program. Hence, travel time calculated here is at best a good first approximation.

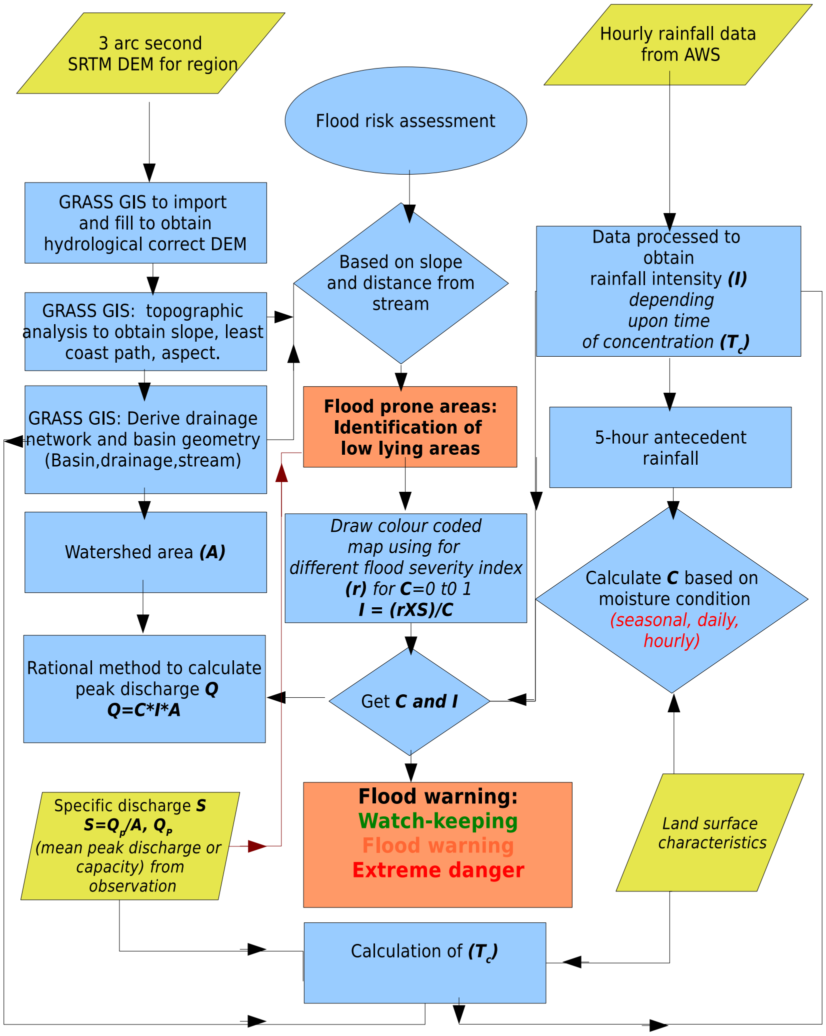


Figure 4: Flowchart of the flood risk assessment method.

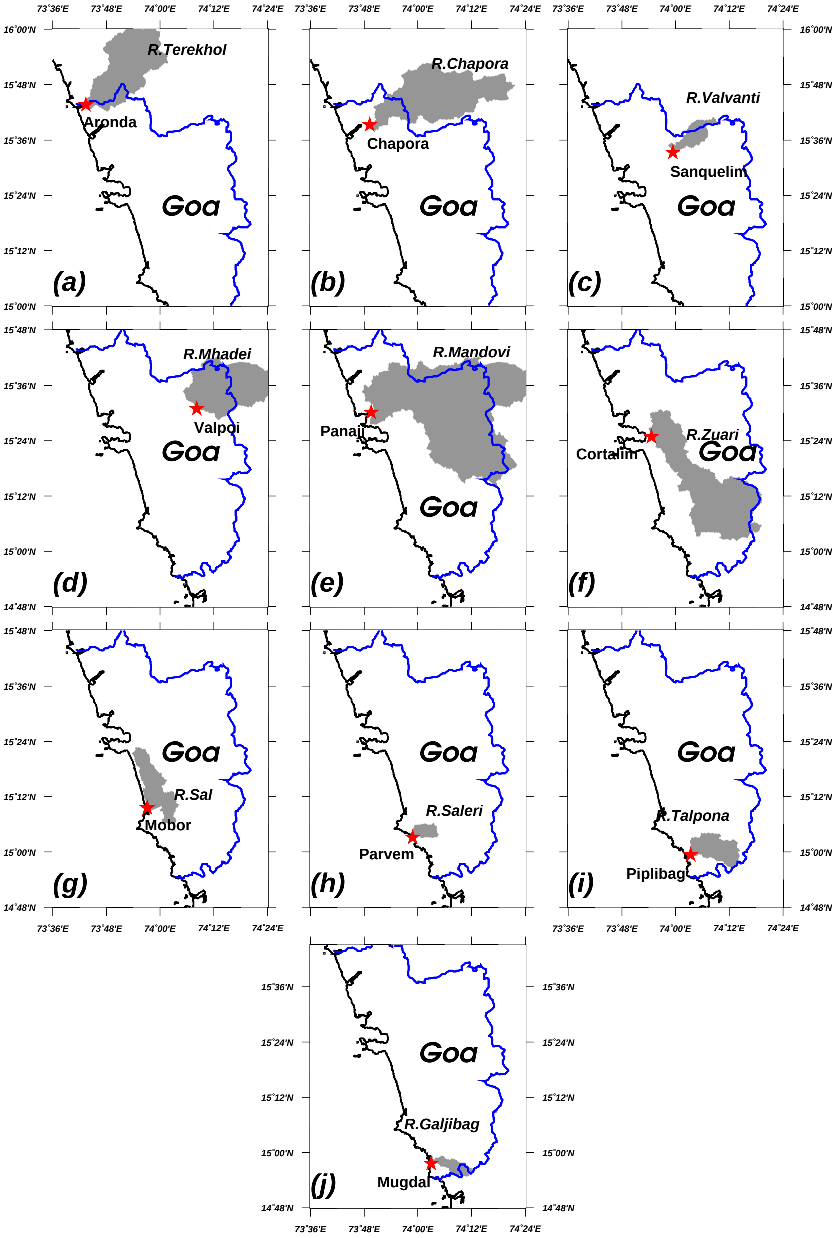


Figure 5: The area plotted in grey is the watershed area over the location (red star) mentioned in Table 1 for Goa rivers. The place name mentioned on the map is nearest town/city. Watershed area calculated for (a) Terekhol river near Aronda, (b) Chapora river near Chapora, (c) Valvanti river near Sanquelim, (d) Mhadei river near Valpoi, (e) Mandovi river near Panaji, (f) Zuari river near Cortalim, (g) Sal river near Mobor, (h) Saleri river near Parvem, (i) Talpona river near Piplibag, (j) Galjibag river near Mugdal.

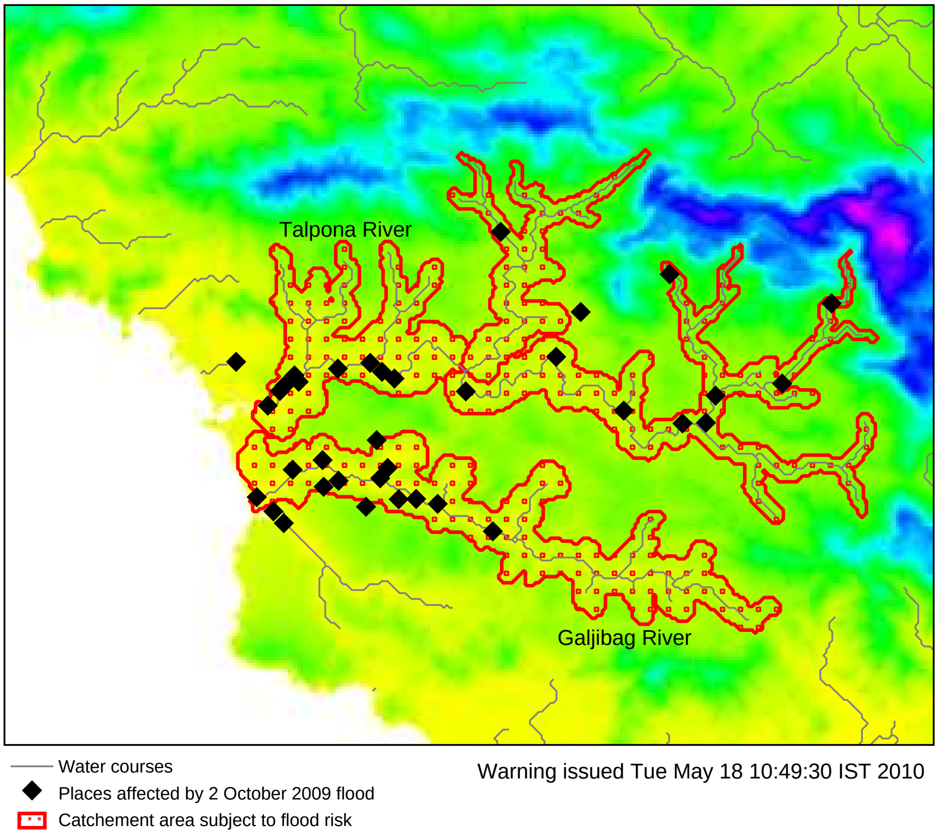


Figure 6: A map of low-lying areas in Talpona and Galjibag river basin. Places affected on floods of 2 October 2009 are also marked for comparison. A script which was used to plot this map is included in Appendix F, which can be modified easily to plot such maps for any region.

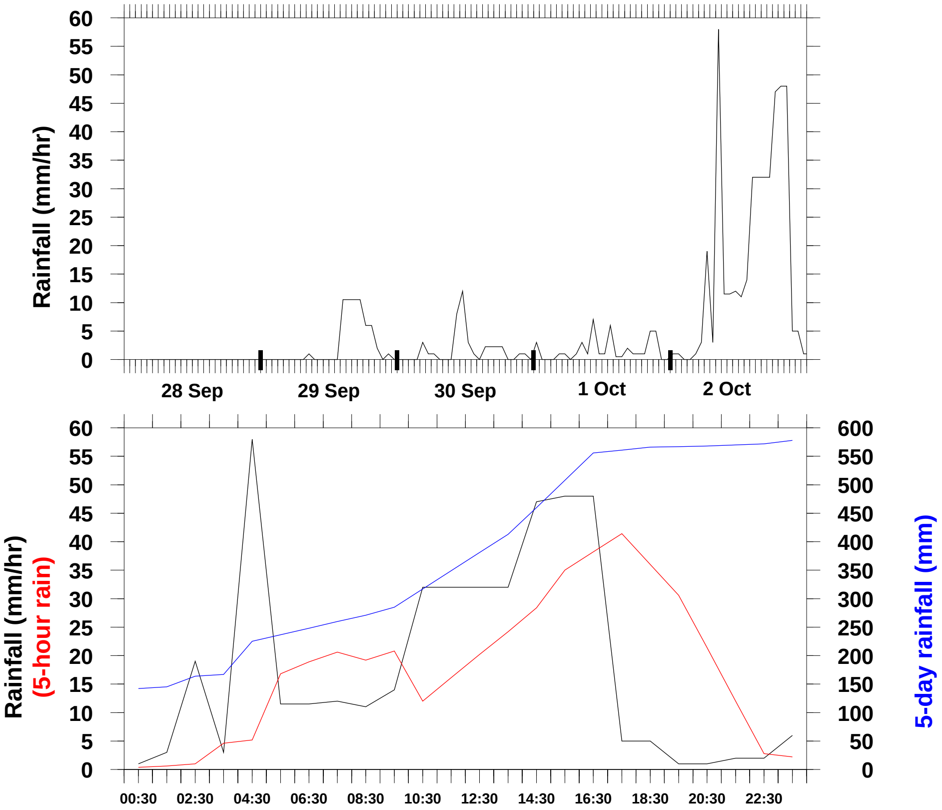


Figure 7: In top panel, interpolated rainfall intensity (mm hr^{-1}; black curve) from Canacona AWS for 28 September to 2 October is plotted. In bottom panel, rainfall intensity (black curve) for only 2 October is plotted. Last 5-day rainfall (mm; blue curve) and last 5-hour rainfall intensity (mm hr^{-1}; red curve) is used to determine the runoff coefficient C.

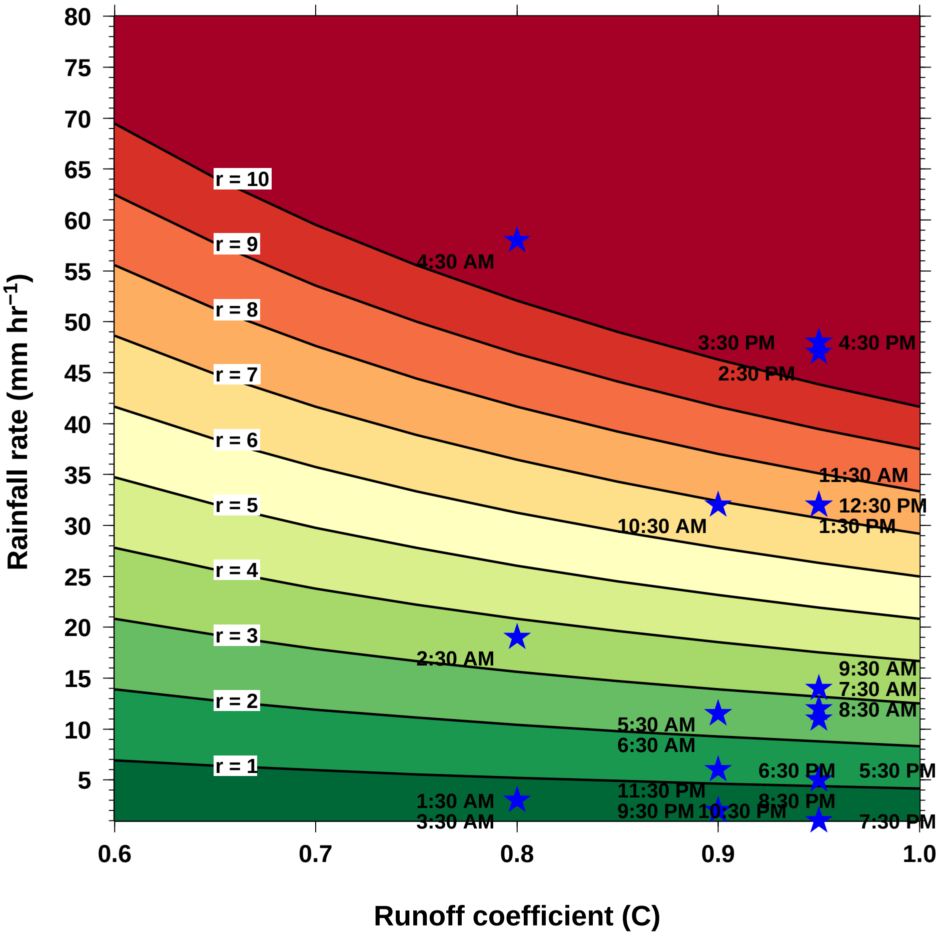
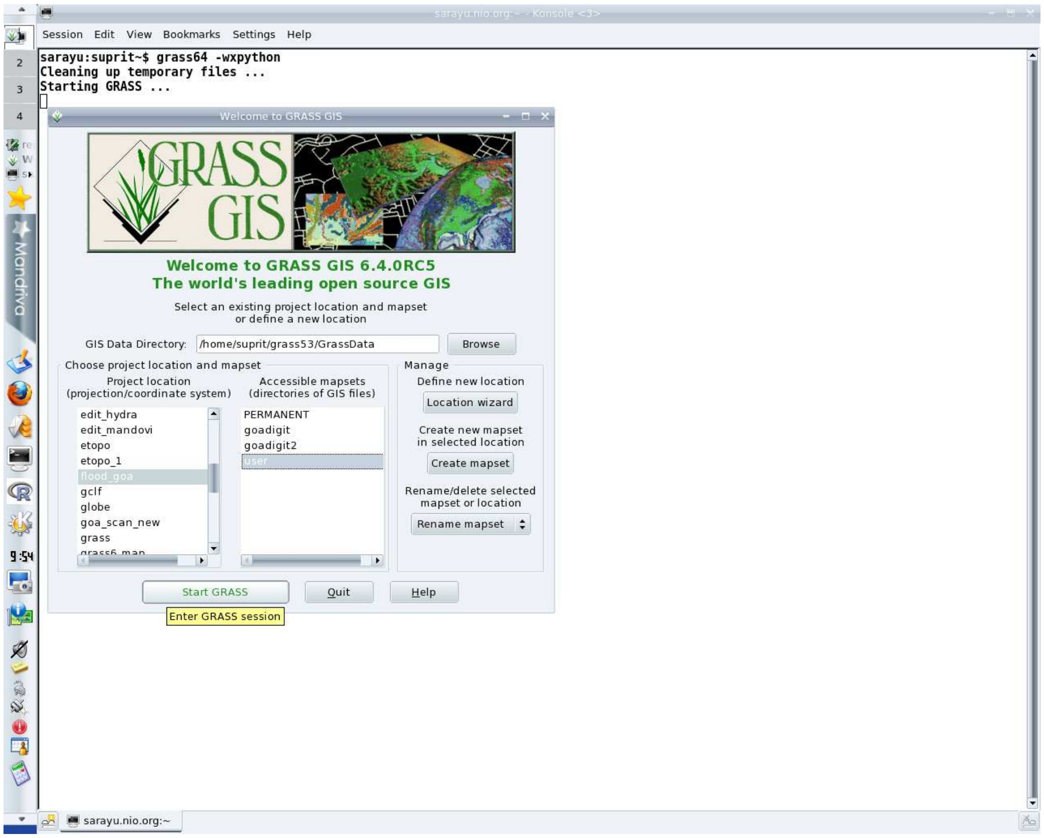


Figure 8: Based on the *rational method* (Equation (4.2)),a colour coded flood warning chart for the Talpona river basin for different values of r is plotted. Values of C is plotted on X-axis along with the rainfall on Y-axis. As, rain rate data arrive from AWS, C is estimated and accordingly a point (blue star) is placed on the graph. The green zone ($q > 4$) denotes watch-keeping mode. The transition between green to red (orange zone) is action one, where warning should be issued, if rainfall rate persisted for few hours.The red zone denotes severe flood ($q > 10$) situation, accordingly deployment of remedial measures is suggested.



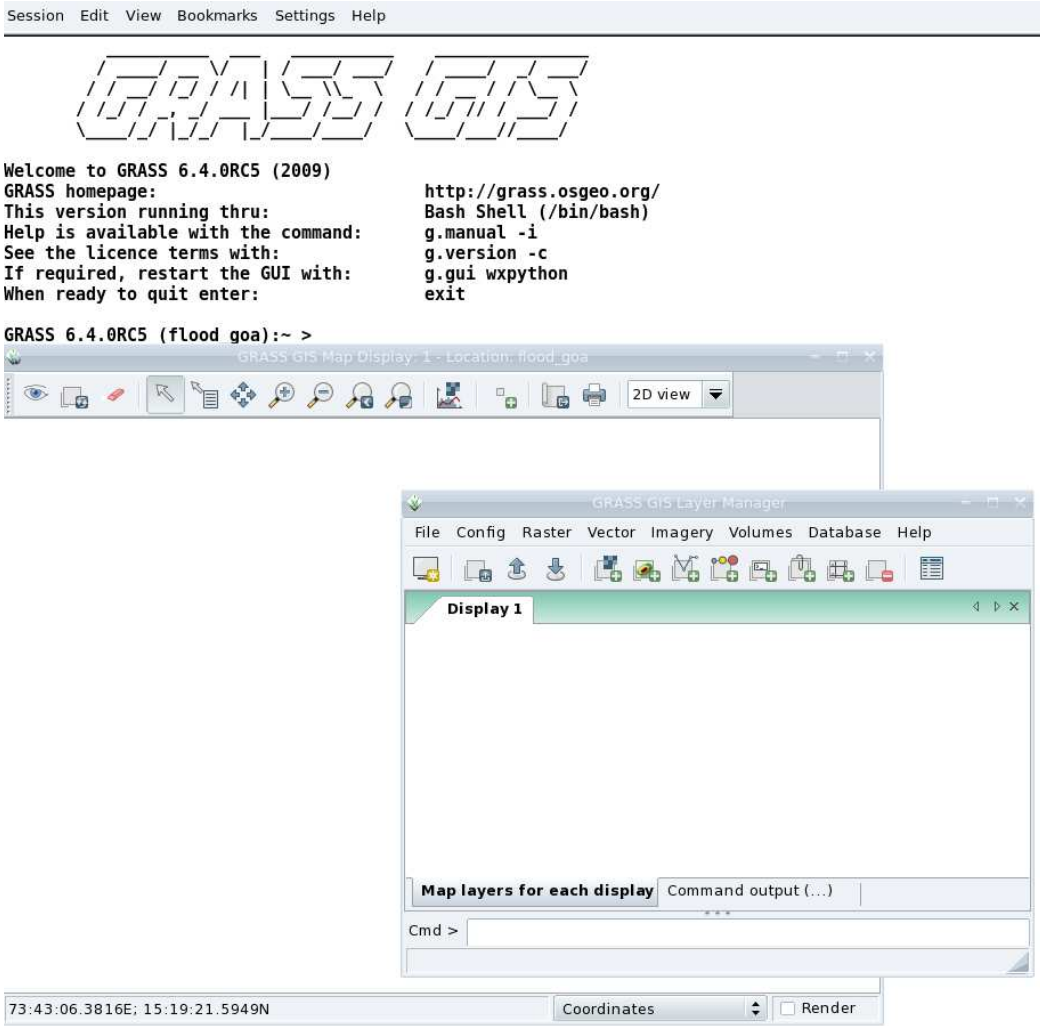
```
sarayu:suprit~$ grass64 -wxpython
Cleaning up temporary files ...
Starting GRASS ...
```

Welcome to GRASS GIS 6.4.0RC5
The world's leading open source GIS

Select an existing project location and mapset
or define a new location

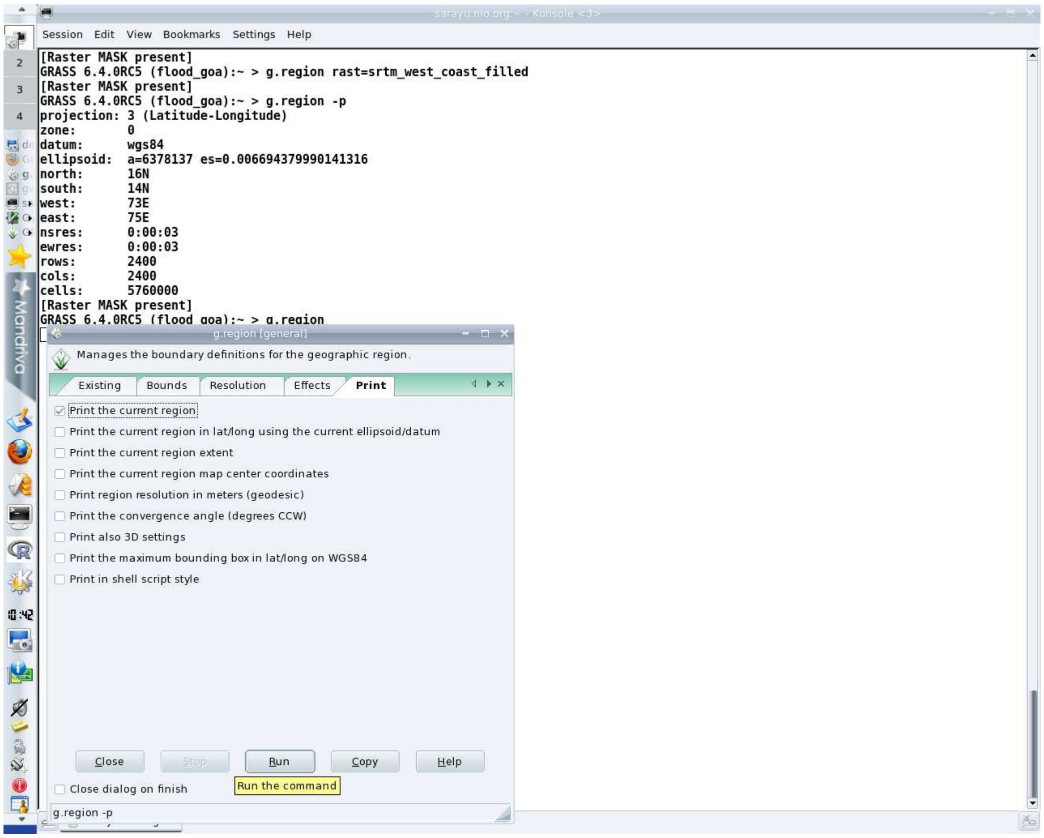
GIS Data Directory: /home/suprit/grass53/GrassData

Figure 9: GRASS startup screen, using wxPython GUI and command line interface (CLI).



```
          __________  ___   __________    _______________
         / ____/ __ \/   | / ___/ ___/   / ____/  _/ ___/
        / / __/ /_/ / /| | \__ \\_  \   / / __ / / \__ \
       / /_/ / _, _/ ___ |___/ /__/ /  / /_/ // / ___/ /
       \____/_/ |_/_/  |_/____/____/   \____/___//____/

Welcome to GRASS 6.4.0RC5 (2009)
GRASS homepage:                         http://grass.osgeo.org/
This version running thru:              Bash Shell (/bin/bash)
Help is available with the command:     g.manual -i
See the licence terms with:             g.version -c
If required, restart the GUI with:      g.gui wxpython
When ready to quit enter:               exit

GRASS 6.4.0RC5 (flood goa):~ >
```

Figure 10: Selecting the location and mapset.



```
[Raster MASK present]
GRASS 6.4.0RC5 (flood_goa):~ > g.region rast=srtm_west_coast_filled
[Raster MASK present]
GRASS 6.4.0RC5 (flood_goa):~ > g.region -p
projection: 3 (Latitude-Longitude)
zone:       0
datum:      wgs84
ellipsoid:  a=6378137 es=0.006694379990141316
north:      16N
south:      14N
west:       73E
east:       75E
nsres:      0:00:03
ewres:      0:00:03
rows:       2400
cols:       2400
cells:      5760000
[Raster MASK present]
GRASS 6.4.0RC5 (flood_goa):~ > g.region
```

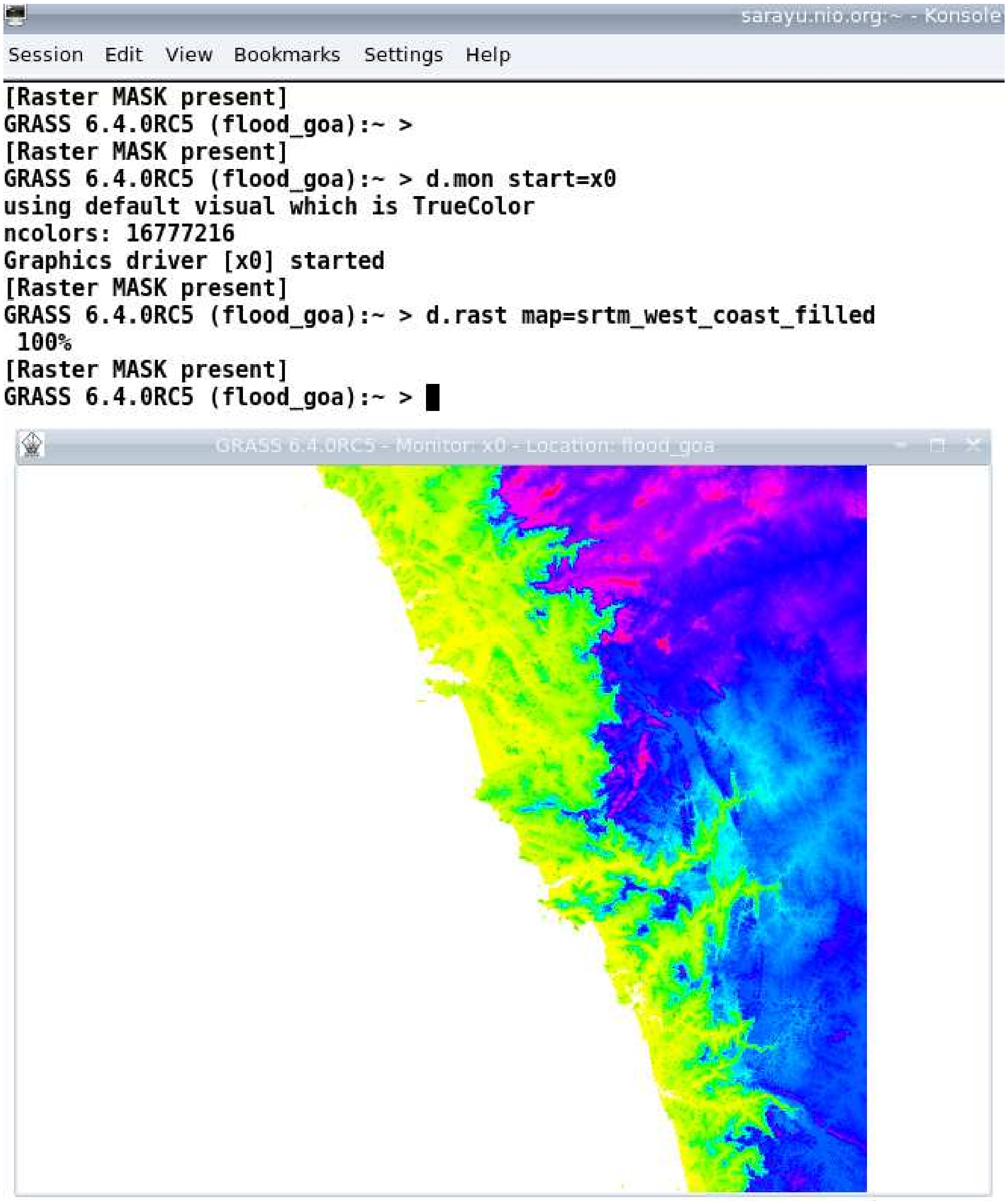
Manages the boundary definitions for the geographic region.

☑ Print the current region
☐ Print the current region in lat/long using the current ellipsoid/datum
☐ Print the current region extent
☐ Print the current region map center coordinates
☐ Print region resolution in meters (geodesic)
☐ Print the convergence angle (degrees CCW)
☐ Print also 3D settings
☐ Print the maximum bounding box in lat/long on WGS84
☐ Print in shell script style

☐ Close dialog on finish

```
g.region -p
```

Figure 11: Selecting the region. Note the GUI and CLI version of same command. GUI version of most of the GRASS GIS commands can be started by running the command without any options. Henceforth, we use CLI only.

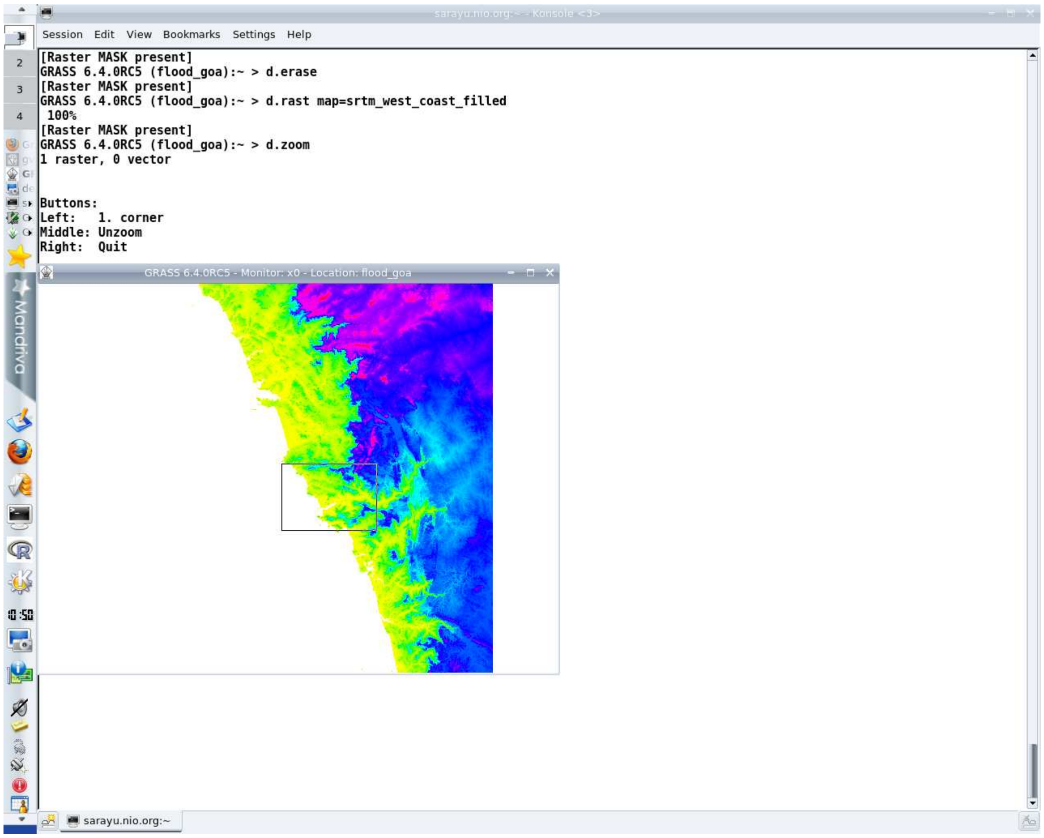


```
[Raster MASK present]
GRASS 6.4.0RC5 (flood_goa):~ >
[Raster MASK present]
GRASS 6.4.0RC5 (flood_goa):~ > d.mon start=x0
using default visual which is TrueColor
ncolors: 16777216
Graphics driver [x0] started
[Raster MASK present]
GRASS 6.4.0RC5 (flood_goa):~ > d.rast map=srtm_west_coast_filled
 100%
[Raster MASK present]
GRASS 6.4.0RC5 (flood_goa):~ > █
```

Figure 12: After opening a GRASS graphics monitor *x0*, SRTM DEM is displayed.

```
GRASS 6.4.0RC5 (flood_goa):~ >
GRASS 6.4.0RC5 (flood_goa):~ > r.mapcalc "mask_map = if (srtm_west_coast_filled > 0, 1, null() )"
 100%
GRASS 6.4.0RC5 (flood_goa):~ > g.copy mask_map,MASK
Copy raster <mask_map@user> to current mapset as <MASK>
[Raster MASK present]
GRASS 6.4.0RC5 (flood_goa):~ > d.rast MASK
 100%
[Raster MASK present]
GRASS 6.4.0RC5 (flood_goa):~ >
```

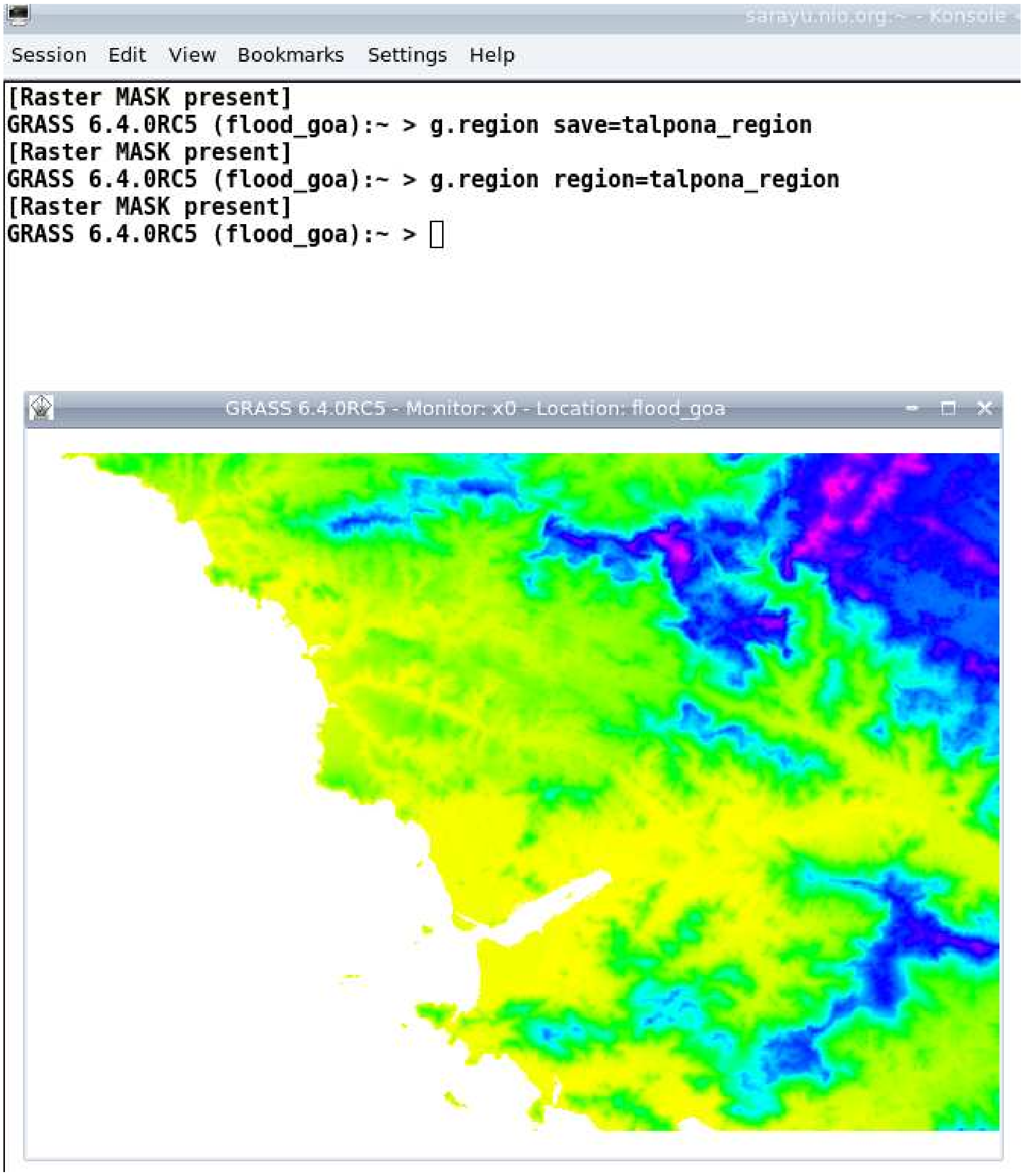
Figure 13: A MASK map is created and displayed.



```
[Raster MASK present]
GRASS 6.4.0RC5 (flood_goa):~ > d.erase
[Raster MASK present]
GRASS 6.4.0RC5 (flood_goa):~ > d.rast map=srtm_west_coast_filled
 100%
[Raster MASK present]
GRASS 6.4.0RC5 (flood_goa):~ > d.zoom
1 raster, 0 vector


Buttons:
Left:   1. corner
Middle: Unzoom
Right:  Quit
```

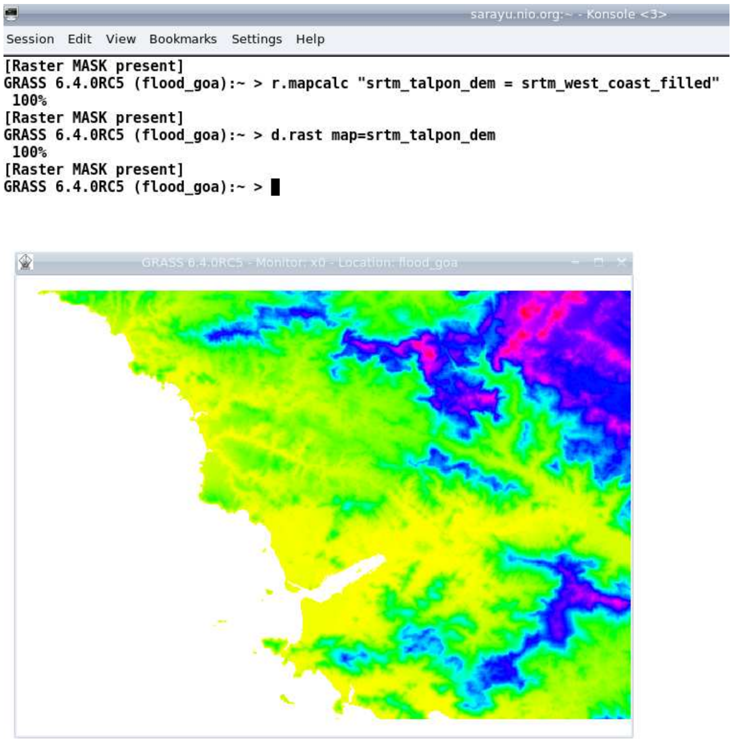
Figure 14: User can zoom to the project area, in this case, we are zooming into the region of Talpona river.

]



```
[Raster MASK present]
GRASS 6.4.0RC5 (flood_goa):~ > g.region save=talpona_region
[Raster MASK present]
GRASS 6.4.0RC5 (flood_goa):~ > g.region region=talpona_region
[Raster MASK present]
GRASS 6.4.0RC5 (flood_goa):~ > 
```

Figure 15: The zoomed region can be saved to revisit later.

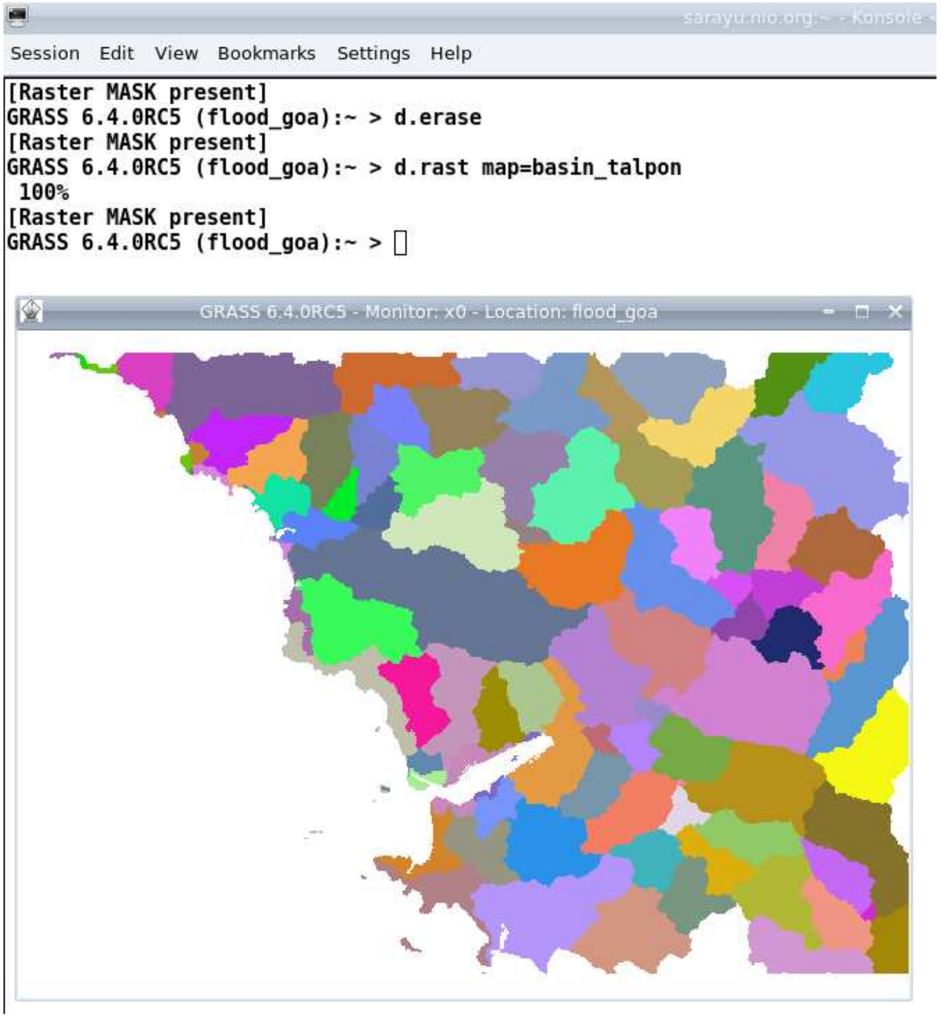


```
[Raster MASK present]
GRASS 6.4.0RC5 (flood_goa):~ > r.mapcalc "srtm_talpon_dem = srtm_west_coast_filled"
 100%
[Raster MASK present]
GRASS 6.4.0RC5 (flood_goa):~ > d.rast map=srtm_talpon_dem
 100%
[Raster MASK present]
GRASS 6.4.0RC5 (flood_goa):~ >
```

Figure 16: From the original big DEM, a small subset pertaining to current project can be saved. This allows smaller file sizes and less computation time.

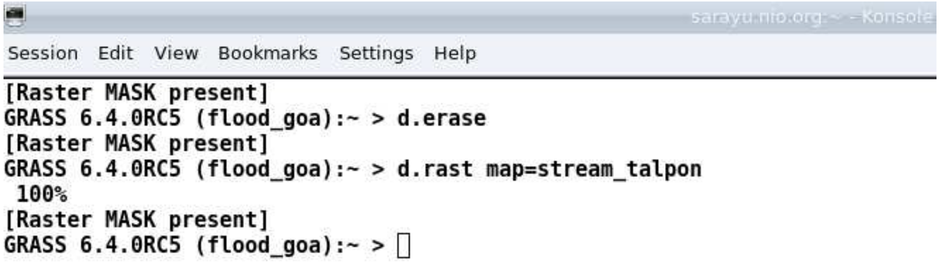
```
[Raster MASK present]
GRASS 6.4.0RC5 (flood_goa):~ > r.watershed --o elevation=srtm_talpon_dem threshold=1000 drainage=drainage_talpon stream=stream_talpon v
isual=visual_talpon basin=basin_talpon
SECTION 1a (of 5): Initiating Memory.
SECTION 1b (of 5): Determining Offmap Flow.
 100%
SECTION 2: A * Search.
 100%
SECTION 3: Accumulating Surface Flow.
 100%
SECTION 4: Watershed determination.
 100%
SECTION 5: Closing Maps.
 100%
[Raster MASK present]
GRASS 6.4.0RC5 (flood_goa):~ > █
```

Figure 17: Executing module *r.watershed* for the Talpona river region.



```
[Raster MASK present]
GRASS 6.4.0RC5 (flood_goa):~ > d.erase
[Raster MASK present]
GRASS 6.4.0RC5 (flood_goa):~ > d.rast map=basin_talpon
 100%
[Raster MASK present]
GRASS 6.4.0RC5 (flood_goa):~ > 
```

Figure 18: Basin map for the selected region. The detail required in basin is controlled by threshold value in *r.watershed* module, e. g., a lot of the sub basins can be grouped together to form a big basin, if threshold is changed to 10000 (threshold is the minimum size of exterior basin). Each basin has a unique category number (thus colour).



```
[Raster MASK present]
GRASS 6.4.0RC5 (flood_goa):~ > d.erase
[Raster MASK present]
GRASS 6.4.0RC5 (flood_goa):~ > d.rast map=stream_talpon
 100%
[Raster MASK present]
GRASS 6.4.0RC5 (flood_goa):~ > ▯
```

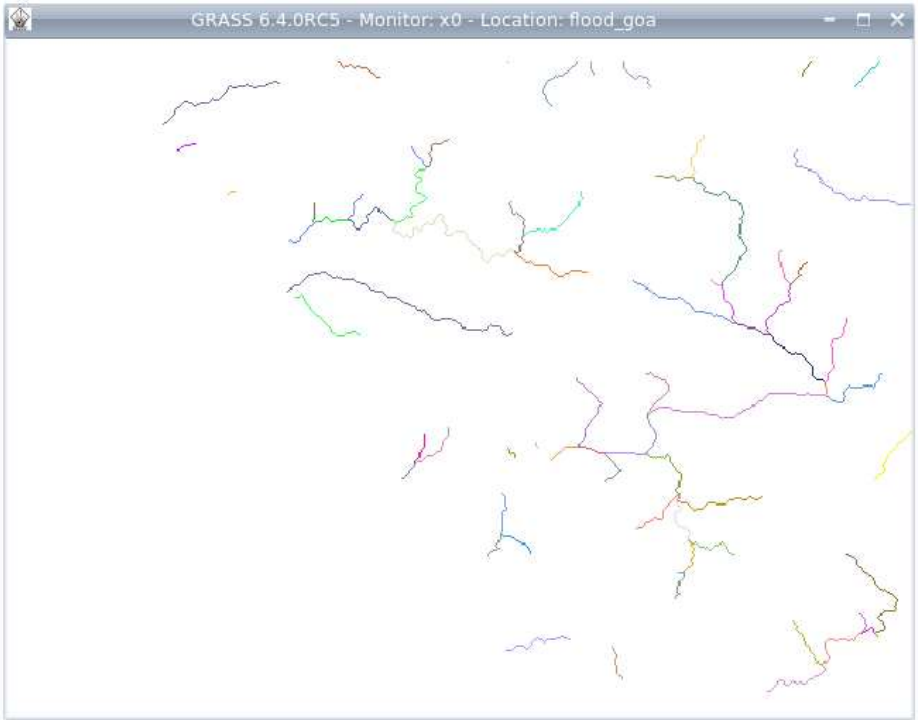
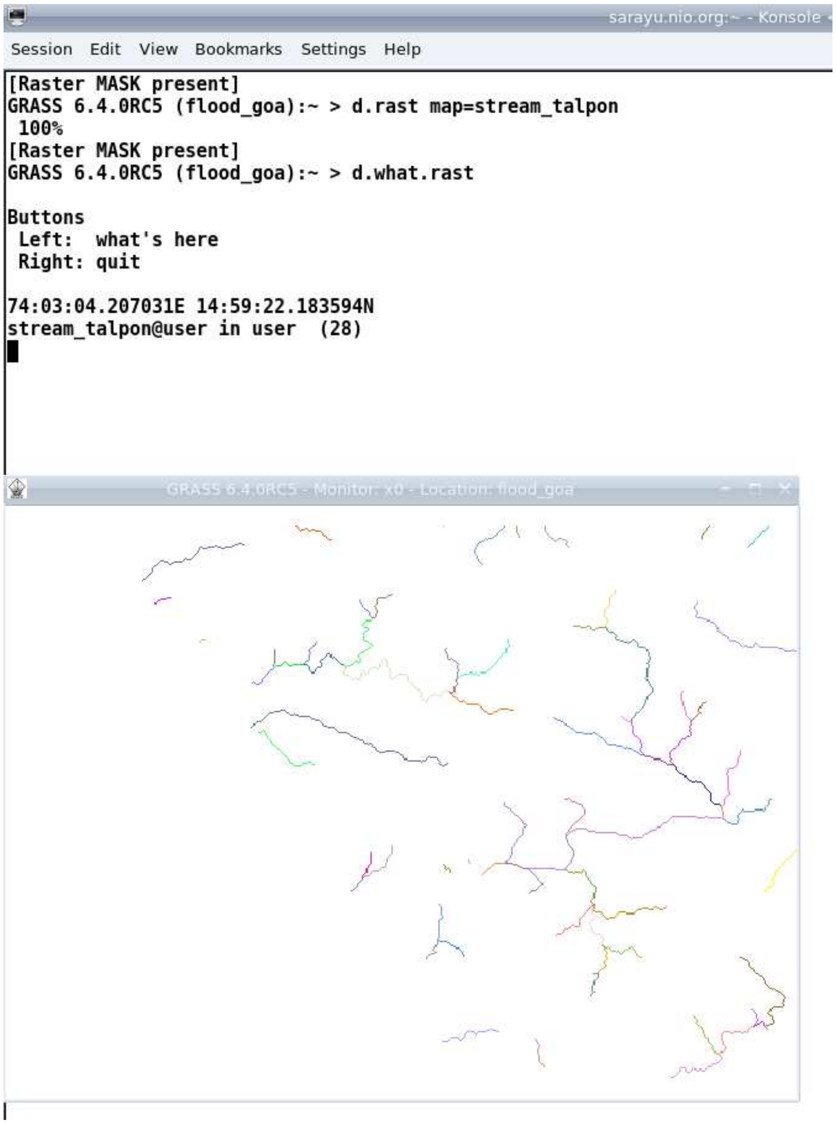
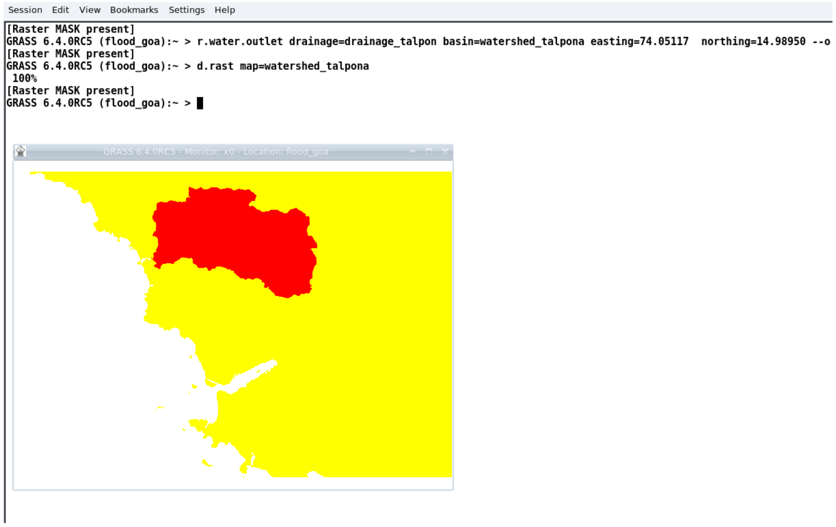


Figure 19: Stream network map for the selected region. Each stream has a category number (shown by different colour), which is same as of corresponding basin. To get a detailed stream network map, threshold need to be lowered as only one stream per basin is shown.



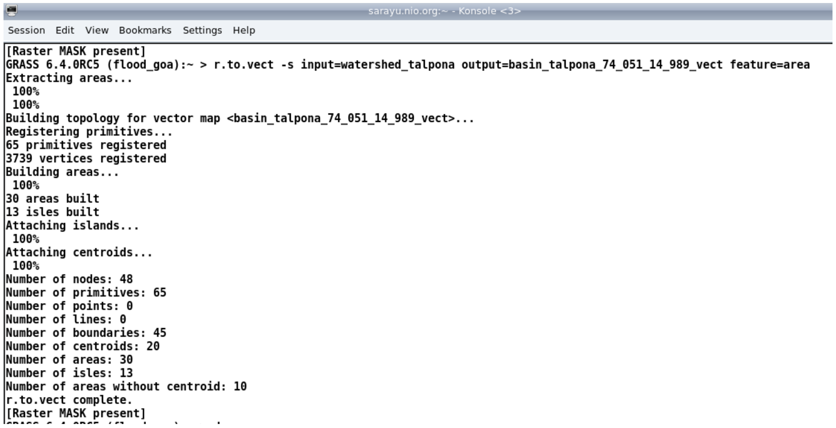
```
[Raster MASK present]
GRASS 6.4.0RC5 (flood_goa):~ > d.rast map=stream_talpon
 100%
[Raster MASK present]
GRASS 6.4.0RC5 (flood_goa):~ > d.what.rast

Buttons
 Left:  what's here
 Right: quit

74:03:04.207031E 14:59:22.183594N
stream_talpon@user in user  (28)
```

Figure 20: Choosing location on the Talpona river. For this example, location is chosen on the mouth of the river.



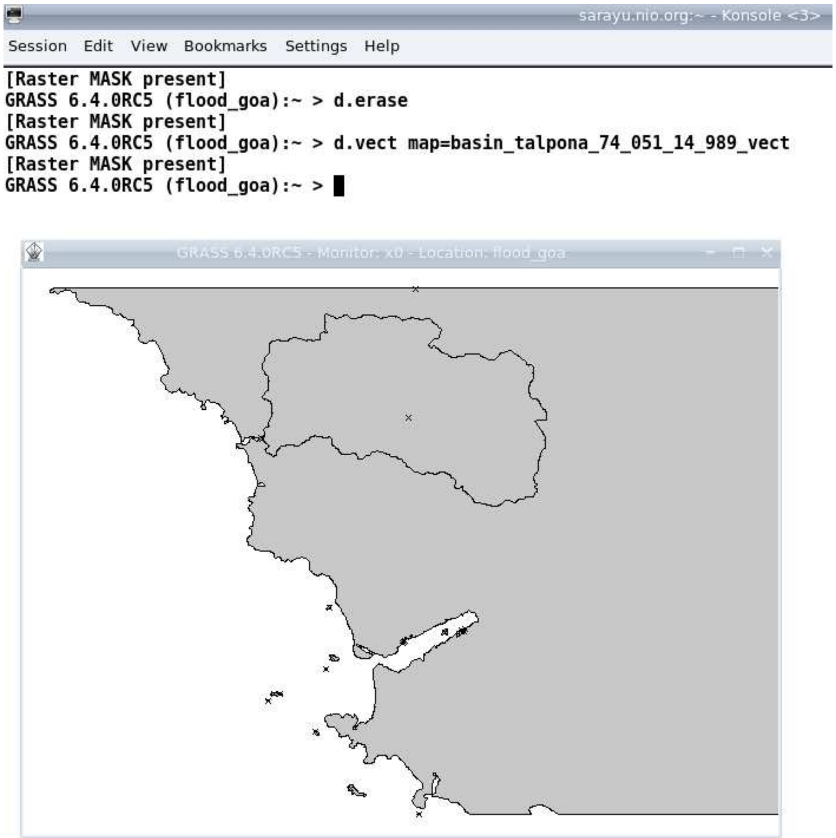
```
[Raster MASK present]
GRASS 6.4.0RC5 (flood_goa):~ > r.water.outlet drainage=drainage_talpon basin=watershed_talpona easting=74.05117  northing=14.98950 --o
[Raster MASK present]
GRASS 6.4.0RC5 (flood_goa):~ > d.rast map=watershed_talpona
 100%
[Raster MASK present]
GRASS 6.4.0RC5 (flood_goa):~ > 
```

Figure 21: Creating watershed area over the selected location. The area plotted in red is the watershed area over the selected location.



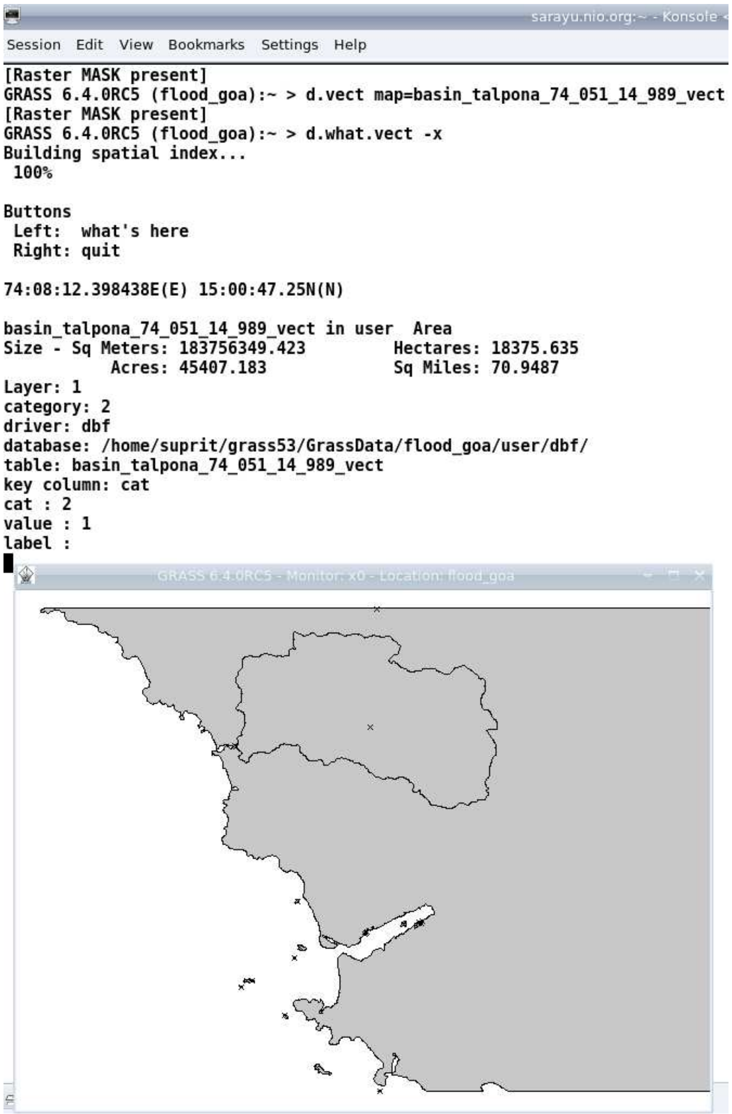
```
[Raster MASK present]
GRASS 6.4.0RC5 (flood_goa):~ > r.to.vect -s input=watershed_talpona output=basin_talpona_74_051_14_989_vect feature=area
Extracting areas...
 100%
 100%
Building topology for vector map <basin_talpona_74_051_14_989_vect>...
Registering primitives...
65 primitives registered
3739 vertices registered
Building areas...
 100%
30 areas built
13 isles built
Attaching islands...
 100%
Attaching centroids...
 100%
Number of nodes: 48
Number of primitives: 65
Number of points: 0
Number of lines: 0
Number of boundaries: 45
Number of centroids: 20
Number of areas: 30
Number of isles: 13
Number of areas without centroid: 10
r.to.vect complete.
[Raster MASK present]
```

Figure 22: Converting raster map of watershed to vector map.



```
[Raster MASK present]
GRASS 6.4.0RC5 (flood_goa):~ > d.erase
[Raster MASK present]
GRASS 6.4.0RC5 (flood_goa):~ > d.vect map=basin_talpona_74_051_14_989_vect
[Raster MASK present]
GRASS 6.4.0RC5 (flood_goa):~ > █
```

Figure 23: Displaying vector watershed map. The thin black line marks the watershed divide and "x" marked inside is centre (centroid) of the area.



```
[Raster MASK present]
GRASS 6.4.0RC5 (flood_goa):~ > d.vect map=basin_talpona_74_051_14_989_vect
[Raster MASK present]
GRASS 6.4.0RC5 (flood_goa):~ > d.what.vect -x
Building spatial index...
 100%

Buttons
 Left:  what's here
 Right: quit

74:08:12.398438E(E) 15:00:47.25N(N)

basin_talpona_74_051_14_989_vect in user  Area
Size - Sq Meters: 183756349.423        Hectares: 18375.635
           Acres: 45407.183            Sq Miles: 70.9487
Layer: 1
category: 2
driver: dbf
database: /home/suprit/grass53/GrassData/flood_goa/user/dbf/
table: basin_talpona_74_051_14_989_vect
key column: cat
cat : 2
value : 1
label :
```

Figure 24: Querying the vector map will give the area of the watershed. Area is given in m^2, hectares, square miles and acres.

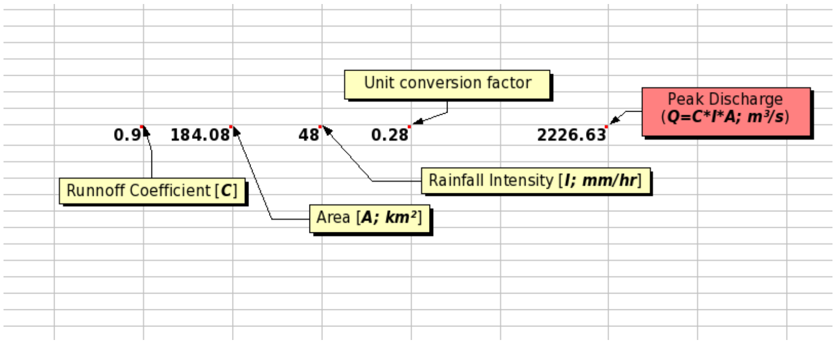


Figure 25: *Rational method* calculation on a spreadsheet software. The area is converted into km^2 from the earlier output.