Water Resources Management manuscript No.
(will be inserted by the editor)

Application of GIS for evaluation and design of watershed guidelines

R. S. Bhalla · Neil W. Pelkey · K. V. Devi Prasad

Received: August 2008 / Accepted: June 2010

Abstract We analyse the suitability of Government of India's 2003 and 2008 common guidelines for prioritising micro-watersheds for restoration. These guidelines attempt to balance the need for improved hydraulic function with poverty alleviation and agricultural productivity. To do so, they provide a set of sub-criteria for prioritising micro-watersheds for treatment. We ranked the micro-watersheds in the Kalivelli basin in South India based on these sub-criteria. We then compared the 2003 with the 2008 guidelines using GIS and spatial statistics. Visual inspection of the resulting digital maps and spatial autocorrelation analysis showed that individual sub-criteria within a guideline were highly positively auto correlated. Spatial cross-correlations using Mantels test between sub-criteria in the same guidelines produced negative results however. Very different watersheds would have been selected for treatment using the 2003 vs. the 2008 guidelines. While this could have been evidence that the 2008 guidelines were an improvement over the 2003 guidelines, comparing the planning outcomes did not support this conclusion. We conclude that criteria used to select micro-watersheds for hydrologic treatment should be re-formulated emphasizing efficient resource use and improved hydraulic function prior to social and economic concerns. Finally, we argue that a combined GIS and spatial analysis approach is amenable to quickly evaluating watershed selection criteria as well as assessing post implementation outcomes.

Keywords Watershed restoration, multiple criteria ranking, decision support, rural development.

R. S. Bhalla
Foundation for Ecological Research, Advocacy and Learning, No.27, 2nd Cross Appavou Nagar, Vazhakularm, Pondicherry 605 012, India
E-mail: bhalla@feralindia.org
Tel.:+91-413-2671566, Fax: +91-413-2671567

Neil W Pelkey
Earth and Environmental Sciences and Information Technology, Juniata College, Huntingdon, Pennsylvania, USA.

K. V. Devi Prasad
School of Ecology and Environmental Sciences, Pondicherry University, R.Venkataraman Nagar, Kalapet, Puducherry 605 014

1 Introduction

The daily lives of six hundred million people in India depend directly on functioning watersheds providing drinking water, irrigation, energy, groundwater recharge and inland fisheries. Mistakes in watershed prioritisation and planning can have serious local ramifications. When such mistakes are institutionalised on a national scale, the results can be tragic.

We explore the potential for institutionalised mistakes in water planning by examining the common guidelines for watershed management (common guidelines) which are released by the Government of India (GoI), Ministry of Rural Development. These are the most widely used guidelines for designing, funding, and implementing watershed development projects in India. They provide a set of criteria on the basis of which hydrological subdivisions of a watershed, micro-watersheds, are to be prioritised for treatment. Four versions of the common guidelines were released between 1994 and 2010. Of these the first three were released in 1994, 2001 and 2003 respectively (Government of India, 1994, 2001b, 2003) and provided a nearly identical set of eight criteria (Tab. 2). The fourth and latest version was released in 2008 (Government of India, 2008b) and three of its eight criteria (Tab. 3) differed from the earlier guidelines.

We refer to these hereafter as the sub-criteria of the old and new criteria set. These subcriteria appear to make sense prima facie and rank micro-watersheds on the basis of poverty levels, water shortage, extent of degraded and common lands etc. Micro-watersheds with the highest ranks are then supposed to receive the lion's share of funding.

We apply them to the watershed of the Kalivelli lake to determine which would receive the most attention under the current guidelines. We also explore the contradiction in the rankings between the sub-criteria and address the problems spatial aggregation of criteria and missing data create in these prioritisation schemes.

1.1 Goals of watershed development in India

Watershed restoration efforts in India have sought to balance poverty alleviation against conservation, and local governance vs technical expertise. Poverty alleviation is often central to any GoI effort and watershed development is no exception. India's Planning Commission has explicitly made the link between degraded watershed areas and poverty. The 2002 planning report states that - degraded watershed "correlate strongly with the incidence of poverty" (Government of India, 2002).

Since poverty alleviation was central to the guidelines, criteria used to select microwatersheds for restoration were designed to reduce poverty by increasing agricultural productivity and access to water and biomass from common lands. While these should have been consistent with Kerr's goal of managing "hydrological relationships to optimise resource use for conservation, productivity, and poverty alleviation" (Kerr et al, 2007), literature suggests this was not the case. Kerr et al (2002), found that the hype surrounding watershed development projects was based on few extraordinary success stories. In most cases however serious issues of inequity between up and downstream stakeholders remained. He revisited the topic in 2006. However doubts remained in the manner benefits of watershed development projects were allocated among poor and weaker sections (Kerr et al, 2007). Bhandari et al (2007), reviewed a range of programmes of the government of India for land reclamation and restoration. They traced the evolution of the programmes over the years and the attempts made to integrate them under a single framework. They further noted that the watershed programmes form an important part of the government's "anti-poverty strategy in rural India".

Watershed development has also had mixed success as a conservation tool. Reddy (2006), found that "the crux of the issue rests in better implementation". He observed that the latest guidelines were very similar to earlier ones and that only 15-20 percent of the programmes performed satisfactorily. A similar conclusion was reached by Deshpande (2008) and Vaidyanathan (2006). They felt that the guidelines were limited to providing detailed information about institutional arrangements. However, "the state of technical knowledge regarding the physical improvements, management of lands and measures to achieve optimal productivity appropriate to different situations leaves much to be desired" (Vaidyanathan, 2006).

Instead, the framework evolved in the common guidelines focused on building local institutions for resource management which was in tune with the understanding that "projects might work better in a village-based microwatershed" (Kerr et al, 2007). These local governance versus technical expertise trade-offs have led to additional issues. Kerr (2002) found that purely technical interventions often fared worse than participatory approaches while a mix of technical and participatory approaches provided the best results. Gosain and Rao (2004) also found the the assessment and evaluation process was not conducive to appropriate design and interventions.

Lack of financial resources is often the limiting factor for success in implementation (Ostrom, 1990; Sabatier and Pelkey, 1987). But that has not been the case in India. Watershed development has played a growing role in the rural development outlays leading to a marked increase both coverage areas and actual expenditure. The funds released under the integrated wastelands development programme (IWDP) alone increased 274 fold between the period 1995-96 to 2006-07 (Fig. 1). The Parathasarathy Commission Report (Government of India, 2006), which formulated the latest "Neeranchal" guidelines reccommends that Rs.10,000/- crores (over 2 billion USD) be allocated each year for the next 15 years to complete all watershed treatment in India by 2020. (Government of India, 2006, pg.48.).

1.2 Prioritisation of watershed areas for restoration

Frameworks and criteria for prioritising watershed are common in academia. The majority of these are based on hydraulic and landscape characteristics. They include watershed models (Mishra et al, 2007a; Behera and Panda, 2006; Gosain and Rao, 2004; Tripathi et al, 2003) and sediment and runoff models (Moreno-Mateos et al, 2010; Patil et al, 2008; Dabral et al, 2008; Bhattacharyya et al, 2008; Mishra et al, 2007b; Pandey, 2007). Most of these tools are integrated with with GIS and remote sensing. However they are highly sophisticated and out of the reach of most agencies engaged in the actual implementation of these projects (see de Kok et al 2009 for a detailed discussion).

In contrast to academic literature, the common guidelines were based on collating expert opinions from multiple disciplines, including engineering, economics, social welfare, and law. The criteria ended up as a mix of demographic, social and hydraulic priorities. Implementing agencies were expected to use these criteria as the basis for preparation of funding requests. One of their consistent features has been an attempt to integrate rural development and to ensure the involvement of Panchayati Raj (democratic local governance) institutions in the implementation mechanisms. Other key goals have been to address issues of water scarcity, particularly drinking water, but also ground water.

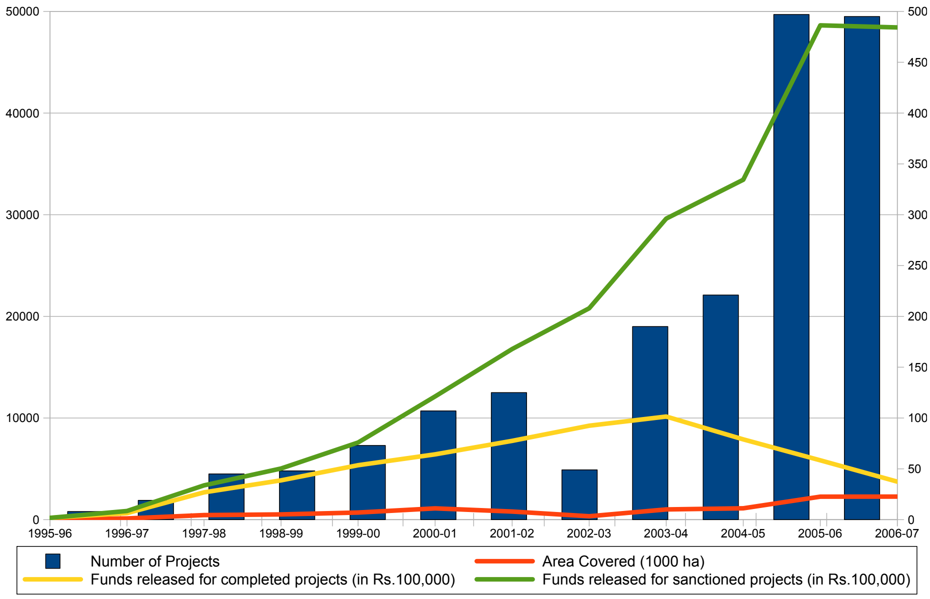


Fig. 1: Allocation of funds and area covered (left y axis) and number of watershed development project (right y axis) under the common guidelines from 1994 to 2007. Source: Government of India 2008a, Annexure iv, v and vi..

In the subsequent section we present a "simple" procedure to prioritise watersheds for restoration under the 1994/2001/2003 and 2008 guidelines. The procedure is spatially explicit and can provide the basis for integration with other spatial data-sets. This includes remotely sensed images and GIS data, like the Tamil Nadu Water And Drainage (TWAD) board, which was used here. The former can help in evaluation of impacts, build models and identify inconsistencies in the baselines. The GIS also ties in with the primary and district census and can easily be integrated with information collected using participatory GIS techniques.

We then use spatial statistics to demonstrate that the sub-criteria forming each criteria set are contradictory. We also demonstrate that the two criteria-sets contradict each other as they rank the micro-watersheds differently. GIS is a decision support tool which is highly relevant for the social but more so for the hydrological or restoration component of the guidelines. It allows us to compare otherwise unrelated processes through their spatial interactions. Using it we could rank the watershed treatment units i.e. micro-watersheds in a spatially explicit manner, allowing us to measure two things: (1) How different sub-criteria in the same criteria set rank the micro-watersheds; whether these ranks are clustered and how they are correlated to each other and (2) Whether the overall ranking of the old and new criteria sets are similar. We could have used a non-spatial procedure to do this, however that would deny us the opportunity to test ranking results in terms of spatial connectivity, which is a fundamental component of watershed processes.

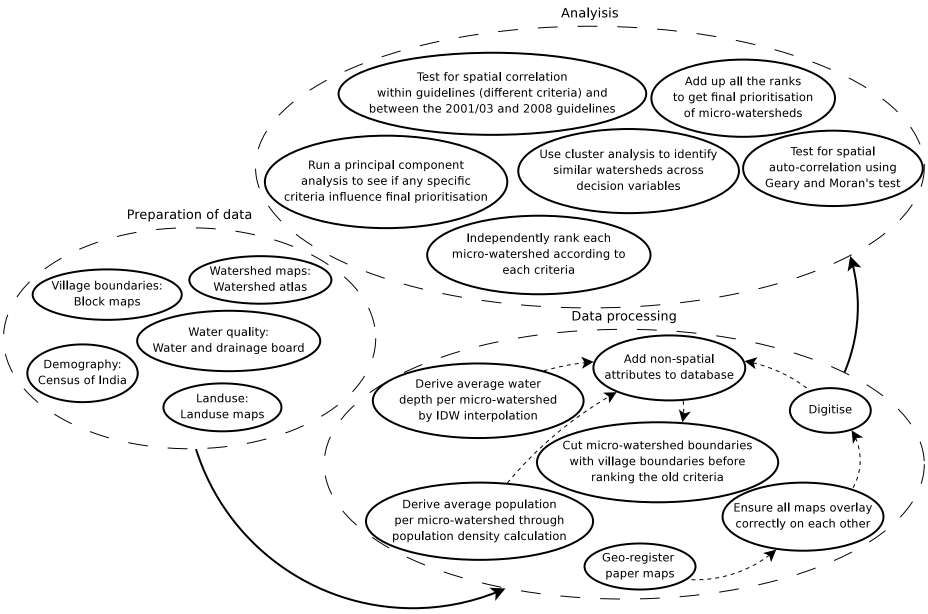


Fig. 2: Methods followed for the analysis.

2 Materials and Methods

Fig. 2 presents the steps involved in organising and analysing the data. Geo-registration, database operations, and mapping were preformed in the Geographical Resource Analysis Support System (GRASS) (GRASS Development Team, 2008), an open source GIS and remote sensing software. PostgreSQL (The Postgresql Development Group, 2007), an open source relational database was used for database operations. All other analysis was done in the R package for statistical computing (R Development Core Team, 2008; Pebesma and Bivand, 2005) using the Emacs speaks statistics (Rossini et al, 2004) and R Commander (Fox et al, 2008). The packages sp.dep (Bivand et al, 2008) and ecodist (Goslee and Urban, 2007), were used for the spatial analysis and psy (Falissard, 2009), polycor (Fox, 2009), Hmisc (Harrell Jr, 2009) and ICSNP (Nordhausen et al, 2010) were used for analysis of correlations, polyserial correlations, data handling and analysis of multivariate outliers. Many of these packages depend on additional libraries. The script used for the analysis has been presented in the supplementary materials (Online Resource 1). It should work on any vector dataset organised in the same way. The script outputs a larger number of tables and figures than those presented here.

2.1 Study area

The study area is a small rainfed watershed (705 sq km, 11°55'N, 79°35'E and 12°10'N, 79°55'E) falling in the Villupuram District of the South Indian state of Tamil Nadu (Fig. 3). The watershed has a high rural population, about 60% of which is below the poverty line. Land use is predominantly agricultural, much of which is irrigated by over 200 minor irrigation tanks with their respective micro-watersheds. These seasonal lakes are linked by

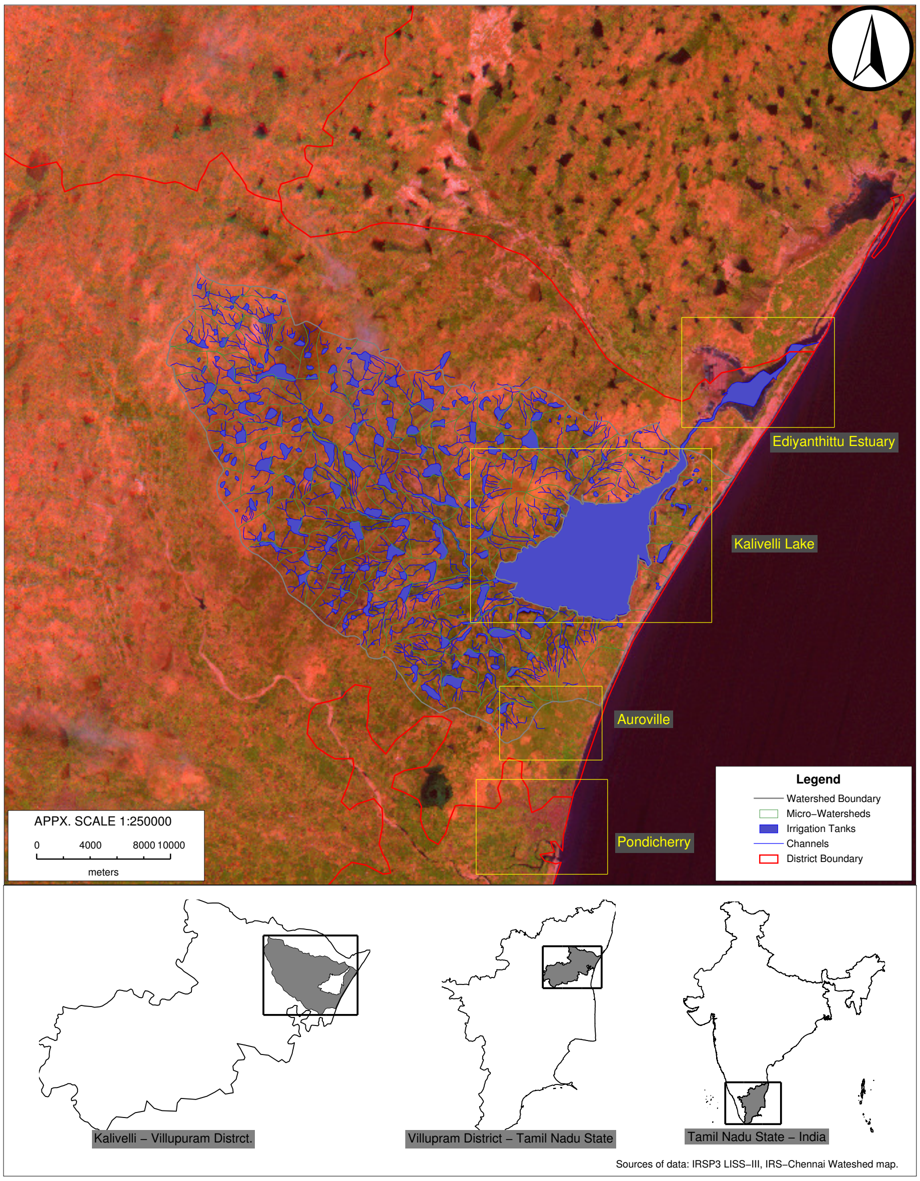


Fig. 3: Location of the study site.

channels which finally drain into the Kalivelli lake, a wetland of national and international importance. Kalivelli is listed under the National Wetland Conservation & Management Programme (Government of India, 2007) and recognised by the IUCN for its ecological value (Pernetta, 1993). The watershed encompasses the international township of Auroville, which like the neighbouring city of Pondicherry, is an important tourist destination. It lies 100 km to the south of Chennai, the fifth most populous city in India with 4.34 million people (Government of India, 2001a). The lake is linked to the Bay of Bengal through a large estuary which supports a number of shrimp farms and an important salt pan industry.

Thus, ecological goods and services of the Kalivelli watershed face a gamut of competing demands. Optimal allocation of resources for the restoration of watershed services is therefore crucial and has a bearing on a large number of stakeholders.

2.2 Preparation of data

Collation of data and maps The common guidelines overcome the complexity and inaccessibility of data required for hydrological planning of watershed restoration. They are based on data that can (largely) be garnered from readily available paper maps, government sources or from India's regional remote sensing centres. Compiling the data from varied sources into formats conducive to multi-criteria decision making was a daunting task. Most maps were only available as printed copies which were in different sizes that were not always consistent with the scale provided and neither their vertical nor horizontal accuracies were published. We therefore had to scan, geo-reference and digitise all the paper maps. This involved collection of hundreds of ground control points using hand held GPS units and co-registration of maps using GIS software. Re-scaling of maps for watershed applications harmonises inconsistencies across scales and datasets. While this does lead to errors, these are known to be a small fraction of the errors leading from non-harmonisation of maps (Myers et al, 1996).

Such work is probably a constraint for many agencies as discussed by Gosain and Rao (2004). In addition, the available maps were often outdated by 5-10 years and had limited consumer accuracies. Tab. 1 provides the list of data used, its sources, limitations as well as the processing done on.

Landuse and administration Watershed and landuse maps were the source of landuse, micro-watersheds and revenue village boundaries. Census data from 2001 (Government of India, 2001a) was attached to the revenue boundaries. The "Lakes, reservoirs, tanks with or without plantations" land use category was used as the proxy for common lands. Areas under this land use category are usually publicly owned. Furthermore they tend to stay publicly owned since encroachments of such lands are specifically prohibited by high court orders. Encroachments on other land cover types are regularised through title deeds which has resulted in continuing reduction in area under common lands in Tamil Nadu (Periasamy, 2010). Therefore our classification reflects the sub-criteria fairly accurately.

Water depth and quality Water quality and depth data from the TWAD board were geo-referenced to match the land use and administrative layers. This information was available as coordinates of test wells located in habitations across the state. 132 such data points were available for the Kalivelli watershed with a mean nearest neighbour distance of 3312.3m using 12 nearest neighbours. The database included depth of water table, various water quality attributes and whether the water was potable or not. To calculate water depth per micro-watershed, we interpolated the depths of the water table to its entire area using these values. The inverse weighted distance method (IDW) (Shapiro, 2006) was used for this calculation with 12 nearest neighbours and a power parameter of 2. While alternative interpolation methods - Kriging, kernel density estimators, running medians, etc. (Cressie, 1993) – were available, we opted for the IDW. It is considered a standard approach and it has been shown

Table 1: Various maps used for the analysis along with their source, scale, projection and kind of conversion done for re-scaling the data set.

Maps/Data	Name	Source	Type of Data	Limitation of Data	Scale	Projection and Units	Conversion Done
Watershed boundaries	Nallavur Watershed 4C1D4	Institute of Remote Sensing (IRS), Chennai	Paper map, printout of vector layer	Scale not provided. Sources of data and processing done not provided. Accuracies not given.	Not specified	WGS 84, Latitude and Longitude	Geo-referenced, digitised, converted to UTM zone 44
Revenue village boundaries	Landuse Map, Vanur Taluk and Marakannam Taluk	IRS, Chennai	Paper map, printout of vector layer	Information about processing and field checks not provided. Accuracies not given.	1:50,000	WGS 84, Latitude and Longitude	Geo-referenced, digitised, converted to UTM zone 44
Land use	Landuse Map. Vanur Taluk and Marakannam Taluk	IRS, Chennai	Paper map, printout of vector layer	Information about processing and field checks not provided. Accuracies not given.	1:50,000	WGS 84, Latitude and Longitude	Geo-referenced, digitised, converted to UTM zone 44
Census	Census 2001	Government of India (2001a)	Database file	Coarse dataset, does not provided settlement wise populations but aggregates to revenue villages.	Not applicable	Not applicable	Census records of each relevant village were linked to the revenue village map
Water quality	Water resources atlas of Tamil Nadu	Tamil Nadu Water and Drainage Board	Vector dataset - points	Improperly geo-registered. Sources of data not provided. Accuracies not given.	Not applicable	WGS 84, Latitude and Longitude	Projected to UTM zone 44, geo-registered to conform to revenue village maps
Ground water depth	Water resources atlas of Tamil Nadu	Tamil Nadu Water and Drainage Board	Vector dataset - points	Improperly geo-registered. Sources of data not provided. Accuracies not given.	Not applicable	WGS 84, Latitude and Longitude	Projected to UTM zone 44. Geo-registered. Average depth per micro-watershed calculated by interpolation using inverse distance weights from vector layer.

to perform well when there is a high coefficient of variation in the “altitudes” (Chaplot et al, 2006). The interpolated depths were then averaged over each micro-watershed.

Drinking water sources identified as non-potable by TWAD were used to identify areas facing shortage of available drinking water. The number of non-potable waters sources was summed for each micro-watershed. We are aware this is a quality indicator and not an indicator of drinking water availability. However this is justified because the water depths from TWAD monitored wells in the watershed ranged from 3 to 30.48 metres with an average of 17.61 metres. The area has hundreds of lakes, ponds, channels and dug wells giving ready access to quantities of water for much of the year. It is the lack of potability that determines the shortage of drinking water in this basin. A village by village survey would be needed to determine actual access to drinking water. This effort would require more resources than we have for this project and certainly more than most agencies have in the Indian context.

Demography The population density of scheduled caste and tribal communities was taken from the Census of India (Government of India, 2001a). The revenue village is the smallest census sampling unit and was used for this purpose. Watershed boundaries, however, do not correspond to revenue village demarcations. We assumed that population densities were uniformly distributed inside the revenue village boundary (dividing the population by the area of the revenue village). This assumption was made for two reasons: 1) Most revenue villages comprise of numerous settlements. Eight to ten settlements, usually demarcated on caste lines, are common. However, coordinates and demographic details of these settlements would require a physical survey. 2) Access to resources in a revenue village is governed by complex relations of caste, economic and political structure. The jurisdiction of settlements over resources is often ill-defined and unclear. It was thus felt that using population densities of these communities in different villages under a watershed was a justified means of estimating their populations under each micro-watershed.

Previous treatment For the sake of simplicity we assumed that none of the watersheds had been treated earlier. Our primary purpose was to test the criteria set for internal consistency as well as against each other. Providing ranks to watersheds around treated areas would have resulted in exclusion of the treated micro-watersheds and higher ranks to each of the bordering ones, making the results more difficult to interpret.

2.3 Ranking micro-watersheds according to the two criteria sets

Each of the sub-criteria are measured on different scales. Re-scaling was therefore necessary prior to a multi criteria comparison. After test runs with other methods such as z-scores, we chose a ranking procedure primarily because it has fewer distributional assumptions than other metrics. See Hajkowicz and Collins (2007); Hajkowicz et al (2000) for a review of multiple criteria analysis frameworks in water resource management. Ranking of the micro-watersheds was done after taking the absolute difference between the observed and optimal values. The formula used was: $rank(|x - opt|)$; where x was the observed value and opt was the optimal value as stated in the sub-criteria.

The map of micro-watershed boundaries with 138 micro-watersheds served as the starting point of the ranking for both the old criteria set (1994, 2001 and 2003 guidelines) and new criteria set (2008 guidelines). However the older criteria set required that the watershed boundaries be re-defined so they honoured revenue village demarcations. A vector overlay was done between the micro-watershed map and the revenue village map which resulted in

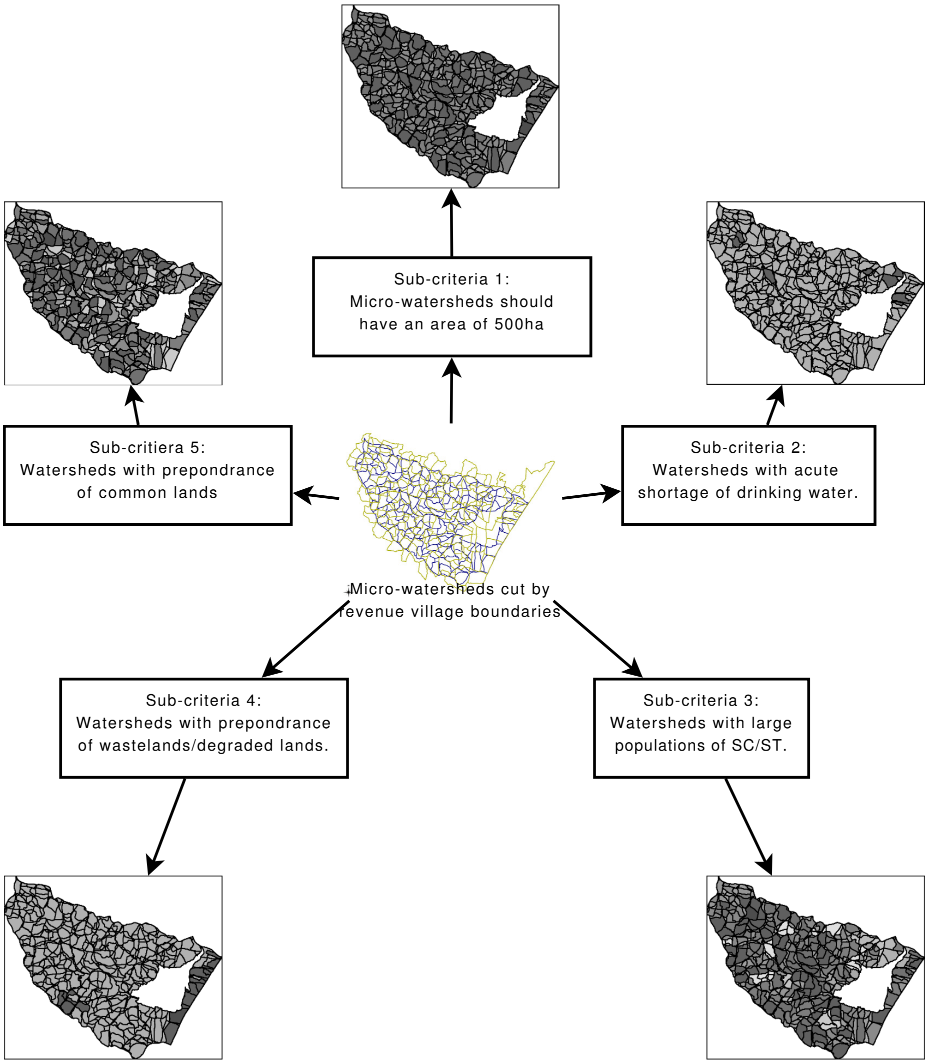


Fig. 4: Ranking procedures for the old criteria set. Darker the colour, higher the rank.

692 micro-watersheds which were used for subsequent ranking. This affected the ranks of identical sub-criteria in the two criteria sets as they were all dependent on area. Tab. 2 and 3 present the old and new criteria sets and data sources used while Fig. 4 and 5 present the ranking procedure. Finally all the ranks were added to get a final prioritisation of areas for treatment, results of which are presented in Fig. 6.

Maps which were created with each micro-watershed associated with a specific sub-criteria rank were used for the subsequent statistical analysis. Thus the sample size for the old criteria set was 692 and that for the new criteria set was 138.

Table 2: Sub-criteria comprising the old criteria set (1994 to 2008) with data and procedures used to transfer them onto a GIS. Sub-criteria listed in italics were not used in the analysis due to uniformity across the watersheds or un-availability of data. The first operation (*) was not listed as a specific criteria but had bearing on the geographic boundaries of the micro-watersheds.

No.	Sub-criteria	Data used	Ranking Procedure
*	In case a watershed falls in two villages, it should be divided into two sub watershed areas confined to the designated villages. Care should be taken to treat both the sub watershed areas simultaneously.	Watershed maps and revenue village maps. Revenue village boundaries can be extracted from block maps at the nearest survey and land records office.	Watershed boundaries were cut by revenue village boundaries using an overlay operation.
1	Watershed area may be about 500ha. However, if on actual survey, a watershed is found to have slightly less or more area, the total area may be taken up for development as a project. Even small contiguous watersheds with an approximate total area of 500 hectares may be taken up for development.	Watershed maps from Institute of Remote Sensing Chennai. Such maps are available from the regional remote sensing centre (RRSC) and the watershed atlas.	The higher the deviation from 500ha the lower the rank.
2	Watershed with acute shortage of drinking water.	Tamil Nadu Water and Drainage Board data was used. Similar data can be obtained from district or state drinking water missions or total sanitation campaign offices.	The number of drinking water sources marked as not potable were taken. Number of such points falling in a given micro-watershed were added.
3	Watershed which has a large population of scheduled castes/scheduled tribes dependent on it.	Landuse maps from IRS Chennai. Such maps are available from RRSC, the National Remote Sensing Centre, Hyderabad and the National bureau of Soil Sciences and Landuse Planning.	The population density of SC/ST communities in a given revenue village was calculated. This was averaged to the micro-watershed boundary.
4	Watershed with preponderance of non-forest wastelands/degraded lands.	Land use maps and watershed maps.	Area under category 2 “Wastelands” under the 9 fold land use classification system was used. Forest areas were excluded.
5	Watershed which has a preponderance of common lands. However, in view of the fact that watershed development aims at poverty alleviation by improving productivity of land and generation of employment, projects not having preponderance of common lands may also be considered for scantion provided there is adequate justification.	Land use maps and watershed maps.	Areas under category “Lakes, reservoirs, tanks with or without plantations” were used.
6	*Watersheds where actual wages are significantly lower than the minimum wages.*	*The only way to obtain this data is through primary surveys in all settlements.*	*This sub-criteria was considered uniform throughout the watershed and not used.*
7	*Watershed which is contiguous to another watershed that has already been developed/treated.*	*District Rural Development Agencies have these details.*	*This sub-criteria was not used for this exercise as explained earlier.*
8	*Watersheds where people’s participation is assured through raw materials, cash, contribution on labour etc. for its development as well as for the operation and maintenance of the assets created.*	*This data can only be obtained through primary surveys.*	*This sub-criteria was considered uniform. It is both difficult to quantify and is likely to change based on the efforts put into awareness generation and mobilisation of communities for the project.*

Table 3: Sub-criteria comprising the new criteria set (2008 onwards) with data and procedures used to transfer them onto a GIS. Sub-criteria listed in italics were not used in the analysis due to uniformity across the watersheds or un-availability of data.

No.	Sub-criteria	Data used	Ranking Procedure
1	Acuteness of drinking water scarcity.	Tamil Nadu Water and Drainage (TWAD) Board data was used. Similar data can be obtained from district or state drinking water missions or total sanitation campaign offices.	The number of drinking water sources marked as not potable were taken per micro-watershed. More such sources, higher the rank.
2	Extent of overexploitation of ground water.	TWAD dataset.	Average depths of water sources were calculated for each micro-watershed. Higher the depth, higher the rank.
3	Preponderance of wastelands/degraded lands.	Land use maps and watershed maps.	Area under category 2 "Wastelands" under the 9 fold land use classification system was used. Forest areas were excluded.
4	*Contiguity to another watershed that has already been developed/treated.*	*District Rural Development Agencies have these details.*	*This sub-criteria was not used for this exercise as explained earlier.*
5	*Willingness of village community to make voluntary contributions, enforce equitable social regulations for sharing of common property resources, make equitable distribution of benefits, create arrangements for the operation and maintenance of assets created.*	*This data can only be obtained through primary surveys.*	*This sub-criteria was considered uniform. It is both difficult to quantify and is likely to change based on the efforts put into awareness generation and mobilisation of communities for the project.*
6	Proportion of scheduled castes/scheduled tribes.	Landuse maps from IRS Chennai. Such maps are available from RRSC, the National Remote Sensing Centre, Hyderabad and the National Bureau of Soil Sciences and Landuse Planning.	The population density of SC/ST communities in a given revenue village was calculated. This was averaged to the micro-watershed boundary. Higher the population density the higher the rank.
7	Area of the project should not be covered under assured irrigation.	Landuse maps.	All area outside the land use category "crop land" was used. More the area higher the rank.
8	Productivity potential of the land.	Land use maps.	Area under potentially productive land use categories were added. These were all land-use categories other than wastelands, salt affected lands, salt pans or built up land.

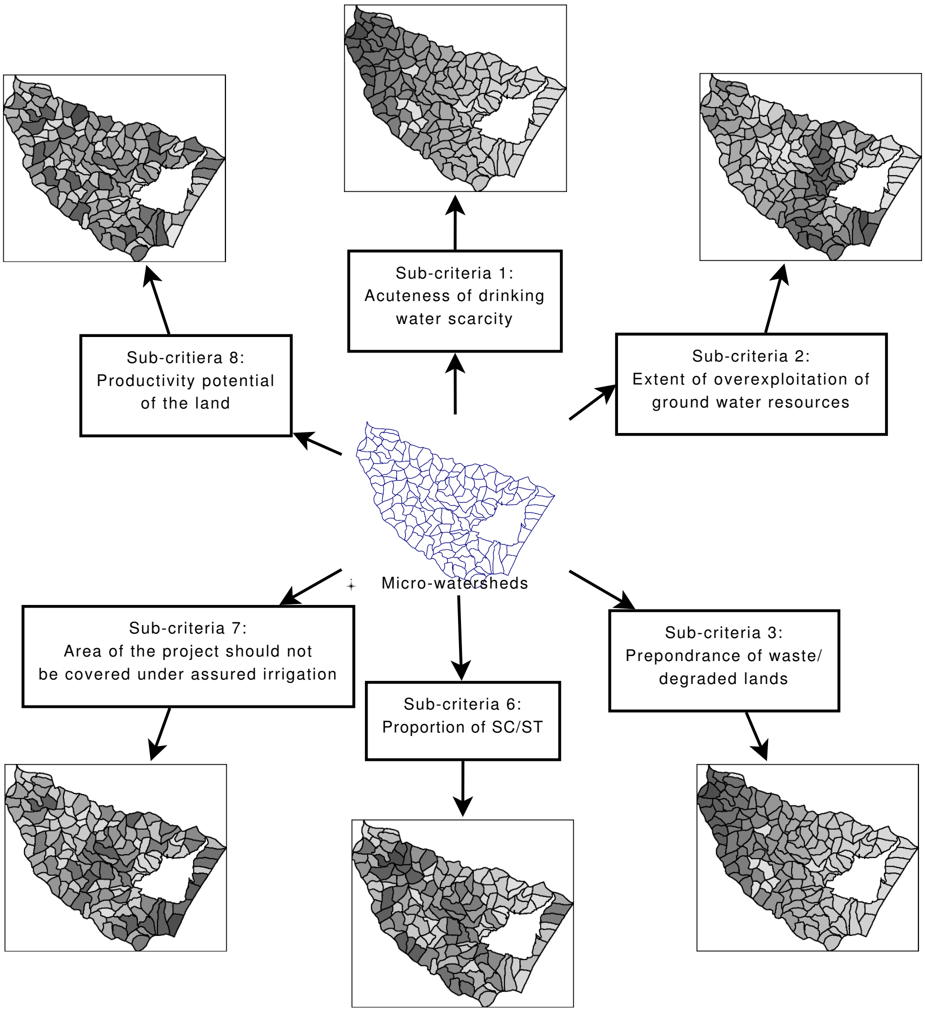


Fig. 5: Ranking procedures for the new criteria set. Darker the colour, higher the rank.

3 Analysis and Results

3.1 Tests for spatial autocorrelation

We first used the Geary's C and Moran's I test for spatial auto-correlation. Results showed that the majority of sub-criteria in both the old and new criteria set were highly autocorrelated (Tab. 4). In other words, micro-watersheds with similar ranks for each sub-criteria tended to be clumped, however these clumps were distinct for each sub-criteria.

Table 4: Results for tests of spatial autocorrelation. All sub-criteria show significant autocorrelation except drinking water (3) in the old set and productivity (8) in the new set for Geary's test. Mantel's test only shows productivity (8) in the new set to be non-significant.

Geary's C Test under randomisation					
Old Criteria Set (1994 to 2008)			New Criteria Set (2008 onwards)		
Ranked Sub-criteria	C statistic	p-value	Ranked Sub-criteria	C statistic	p-value
Watershed area (1)	0.9112	0.0003216	Drinking water (1)	0.2630	< 2.2e-16
Drinking water (2)	0.9752	0.3444	Ground water (2)	0.3607	< 2.2e-16
SC/ST Population (3)	0.7881	< 2.2e-16	Wastelands (3)	0.2630	< 2.2e-16
Wasteland area (4)	0.4288	< 2.2e-16	ST/ST population (6)	0.6639	3.545e-09
Common lands (5)	0.9000	5.352e-05	Non-irrigated lands (7)	0.8323	0.001936
Cumulative rank	0.8907	1.557e-05	Productivity (8)	1.1151	0.9763
			Cumulative rank	0.6925	9.407e-08
Moran's I Test under randomisation					
Ranked Sub-criteria	I statistic	p-value	Ranked Sub-criteria	I statistic	p-value
Watershed area (1)	0.0813	0.0005353	Drinking water (1)	0.7223	< 2.2e-16
Drinking water (2)	0.0603	0.005121	Ground water (2)	0.6265	< 2.2e-16
SC/ST Population (3)	0.1906	1.572e-14	Wastelands (3)	0.7223	< 2.2e-16
Wasteland area (4)	0.4802	< 2.2e-16	ST/ST population (6)	0.3300	2.075e-09
Common lands (5)	0.0722	0.001807	Non-irrigated lands (7)	0.1624	0.001551
Cumulative rank	0.0944	7.481e-05	Productivity (8)	-0.1189	0.9742
			Cumulative rank	0.3159	8.034e-09

3.2 Spatial correlation

We then tested for spatial correlation between sub-criteria of each criteria set using the Mantel test (Tab. 5). Results showed that the sub-criteria were either negatively correlated with each other or not significantly positively correlated. The one exception to this was the positive correlation of new sub-criteria 2 vs 8 (overexploitation of ground water vs productive potential of land). This is consistent with field observations of overexploitation of aquifers in agricultural areas. Comparisons between the old and new criteria sets were not feasible as the geometries of the micro-watersheds were different. i.e. their geographical boundaries were not the same as the older criteria set worked with much smaller units. However the lack of correlation could be due to the different scale of the data used, but without a more accurate data set, which does not exist, we cannot make statistically accurate statement about this. In terms of watershed planning multi-metric indices will fall prey to this problem in general (see Openshaw (1984); Swift et al (2008) for a discussion).

3.3 Principal component analysis

The results of the principal component analysis (PCA) were inconclusive (Tab. 6). PCA analysis is often done as “an interesting” projection of the multidimensional data to fewer

Table 5: Mantel test for spatial correlation between the various sub-criteria of the two criteria sets. Here pval1=one-tailed p-value (null hypothesis: r <= 0), pval2=one-tailed p-value (null hypothesis: r >= 0) and pval3=two-tailed p-value (null hypothesis: r = 0). The majority of the values are negatively correlated or not correlated with the exception of Ground water (2) vs productivity (8) in the new criteria set.

Old Criteria Set (1994 to 2008)				New Criteria Set (2008 onwards)			
Mantel R	pval1	pval2	pval3	Mantel R	pval1	pval2	pval3
Watershed area (1) vs drinking water (2)				Drinking water (1) vs ground water (2)			
0.0296	0.0390	0.9620	0.0780	0.0094	0.3140	0.6870	0.6520
Watershed area (1) vs SC/ST population (3)				Drinking water (1) vs wastelands (3)			
0.6159	0.0010	1.0000	0.0010	1.0000	0.0010	1.0000	0.0010
Watershed area (1) vs wasteland area (3)				Drinking water (1) vs SC/ST population (6)			
0.0280	0.0550	0.9460	0.1000	0.0931	0.0010	1.0000	0.0010
Watershed area (1) vs common lands (4)				Drinking water (1) vs non-irrigated land (7)			
0.3782	0.0010	1.0000	0.0010	0.0164	0.1880	0.8130	0.3850
Watershed area (1) vs sum of ranks				Drinking water (1) vs Cr8			
0.8144	0.0010	1.0000	0.0010	0.0007	0.4890	0.5120	0.9780
Drinking water (2) vs SC/ST population (3)				Drinking water (1) vs sum of ranks			
0.0088	0.2900	0.7110	0.6070	0.3351	0.0010	1.0000	0.0010
Drinking water (2) vs wasteland area (4)				Ground water (2) vs Wastelands (3)			
0.0360	0.1160	0.8850	0.1160	0.0094	0.2940	0.7070	0.6090
Drinking water (2) vs common land (5)				Ground water (2) vs SC/ST population (6)			
0.0347	0.0240	0.9770	0.0240	-0.0100	0.6720	0.3290	0.6200
Drinking water (2) vs sum of ranks				Ground water (2) vs non-irrigated land (7)			
0.1044	0.0010	1.0000	0.0010	0.0265	0.0820	0.9190	0.1500
SC/ST population (3) vs wasteland area (4)				Ground water (2) vs productivity (8)			
0.0129	0.2030	0.7980	0.4280	-0.0405	0.9870	0.0140	0.0430
SC/ST population (3) vs common land (5)				Ground water (2) vs sum of ranks			
0.2658	0.0010	1.0000	0.0010	0.0654	0.0090	0.9920	0.0120
SC/ST population (3) vs sum of ranks				Wastelands (3) vs SC/ST population (6)			
0.7129	0.0010	1.0000	0.0010	0.0931	0.0010	1.0000	0.0010
Wasteland area (4) vs common land (5)				Wastelands (3) vs non-irrigated land (7)			
0.0223	0.0830	0.9180	0.1330	0.0164	0.1990	0.8020	0.3800
Wasteland area (4) vs sum of ranks				Wastelands (3) vs productivity (8)			
0.1569	0.0010	1.0000	0.0010	0.0007	0.4680	0.5330	0.9760
Common land (5) vs sum or ranks				Wastelands (3) vs sum of ranks			
0.5900	0.0010	1.0000	0.0010	0.3351	0.0010	1.0000	0.0010
				SC/ST population (6) vs non-irrigated land (7)			
				0.0688	0.0010	1.0000	0.0010
				SC/ST population (6) vs productivity (8)			
				0.1934	0.0010	1.0000	0.0010
				SC/ST population (6) vs sum of ranks			
				0.4274	0.0010	1.0000	0.0010
				Non-irrigated land (7) vs productivity (8)			
				0.3055	0.0010	1.0000	0.0010
				Non-irrigated land (7) vs sum of ranks			
				0.1842	0.0010	1.0000	0.0010
				Productivity (8) vs sum of ranks			
				0.3126	0.0010	1.0000	0.0010

Table 6: Principal components of hierarchical cluster analysis. In the old set, watershed area (1), SC/ST population (4) and common lands (6) are placed on the first component. Drinking water (3) is placed on the second and wasteland area (5) on the third component. In the new criteria set drinking water (1) and wastelands (3) is place on the first component. Non-irrigated lands (7) and productivity (8) are placed on the second and ground water (2) is placed on the third component.

Old Criteria Set (1994 to 2008)					
Ranked Sub-criteria	Index 1	Index 2	Index 3	Index 4	Index 5
Watershed area (1)	-0.6070	0.0546	-0.0473	-0.1772	0.7713
Drinking water (2)	-0.1167	-0.8977	-0.4098	-0.0854	-0.0731
SC/ST Population (3)	-0.5662	0.1586	0.0346	-0.5593	-0.5832
Wasteland area (4)	-0.1564	-0.3987	0.8962	0.1149	-0.0136
Common lands (5)	-0.5223	0.0847	-0.1594	0.7970	-0.2437
New Criteria Set (2008 onwards)					
Ranked Sub-criteria	Index 1	Index 2	Index 3	Index 4	Index 5
Drinking water (1)	0.6308	0.2222	0.0296	-0.2277	-0.0010
Ground water (2)	0.0328	-0.1806	0.9798	0.0420	0.0672
Wastelands (3)	0.6308	0.2222	0.0296	-0.2277	-0.0010
ST/ST population (6)	0.4095	-0.3526	-0.0915	0.7800	-0.3019
Non-irrigated lands (7)	0.0287	-0.6159	-0.0519	-0.5255	-0.5839
Productivity (8)	0.1858	-0.6041	-0.1648	-0.0995	0.7506

dimensions. It has the interesting feature that it maximises the variance explained in the first component and then successively maximises the remaining variance explained in successive components (Venables et al, 2000). The initial PCA based on the correlations between the ranked data placed three of the sub-criteria for the old criteria set - watershed area (1), SC/ST population (3) and common lands (5) - on the first component. It then placed drinking water (2) on the second component and wasteland area (4) on the third component. Inspection of these components showed that they ranked the same micro-watershed nearly identically and had very low variation in the input variable. The drinking water (2) and wasteland area (4) variables were nearly binary with two distinct data values. For the new dataset the sub-criteria drinking water (1) and wastelands (3) were placed on the first component, non-irrigated lands (7) and productive lands (8) were placed in the second and fifth component. Ground water (2) was placed in the third component, SC/ST (6) and non-irrigated lands (7) on the fourth component.

Pearson's correlations can underestimate the true correlation for non-continuous variables. We therefore re-ran the analysis using polyserial correlation (Lee and Poon, 1987) for the sub-criteria of drinking water and wasteland area[1] with the other variables (Tab. 7). The components for both the new and old criteria set were nearly identical for component 1 and 3 with r's of > 0.95. Component two was substantially different, but still mirrored

[1] Drinking water is sub-criteria 3 and 1 in the old and new criteria set. Wasteland areas is sub-criteria 3 and 5 in the old and new criteria set.

Table 7: A comparison of the Pearson's only and Pearson's Polyserial Correlations for the two criteria. Criteria with binary behaviour (drinking water and wasteland area) showed higher coefficients using the polyserial correlations.

Old Criteria Set (1994 to 2008)						New Criteria Set (2008 onwards)						
Pearson's Correlation only												
Ranked Sub-criteria	Watershed area (1)	Drinking water (3)	SC/ST Population (4)	Wasteland area (5)	Common lands (6)	Ranked Sub-criteria	Drinking water (1)	Ground water (2)	Wastelands (3)	ST/ST population (6)	Non-irrigated lands (7)	Productivity (8)
(1)	1	0.13	0.78	0.15	0.65	(1)	-0.08	0.57	0.65	0.15	-0.47	-0.07
(3)	0.13	1	0.03	0.04	0.1	(2)	-0.13	-0.59	0.05	0.67	-0.42	0.12
(4)	0.78	0.03	1	0.15	0.51	(3)	-0.14	0.53	-0.69	0.31	-0.22	0.28
(5)	0.15	0.04	0.15	1	0.07	(6)	-0.48	-0.18	-0.21	-0.54	-0.57	-0.27
(6)	0.65	0.1	0.51	0.07	1	(7)	-0.59	0.11	-0.02	0.35	0.41	-0.59
						(8)	-0.62	-0.04	0.24	-0.14	0.25	0.69
Pearson and Polyserial Correlation												
Ranked Sub-criteria	Watershed area (1)	Drinking water (3)	SC/ST Population (4)	Wasteland area (5)	Common lands (6)	Ranked Sub-criteria	Drinking water (1)	Ground water (2)	Wastelands (3)	ST/ST population (6)	Non-irrigated lands (7)	Productivity (8)
(1)	1	0.53	0.78	0.35	0.65	(1)	1.00	0.37	0.29	0.18	-0.20	-0.21
(3)	0.53	1	0.1	0.35	0.32	(2)	0.37	1.00	0.30	0.07	0.13	0.08
(4)	0.78	0.1	1	0.51	0.51	(3)	0.29	0.30	1.00	-0.07	-0.39	0.05
(5)	0.35	0.19	0.35	1	0.14	(6)	0.18	0.07	-0.07	1.00	0.26	0.45
(6)	0.65	0.32	0.51	0.14	1	(7)	-0.20	0.13	-0.39	0.26	1.00	0.57
						(8)	-0.21	0.08	0.05	0.45	0.57	1.00

component two for the high ranked watersheds. The PCA gave no new interesting insights into the rankings, and thus we abandoned it in favour of using the original data.[2]

3.4 Cluster analysis

We then used hierarchical cluster analysis to identify watershed that were similar across the decision variables. The resulting cluster dendrogram, however, was illegible due to the high

[2] The script (Online Resource 1) runs multivariate analysis including Mahalanobis distances as a measure of multivariate outliers. However results remained non-conclusive.

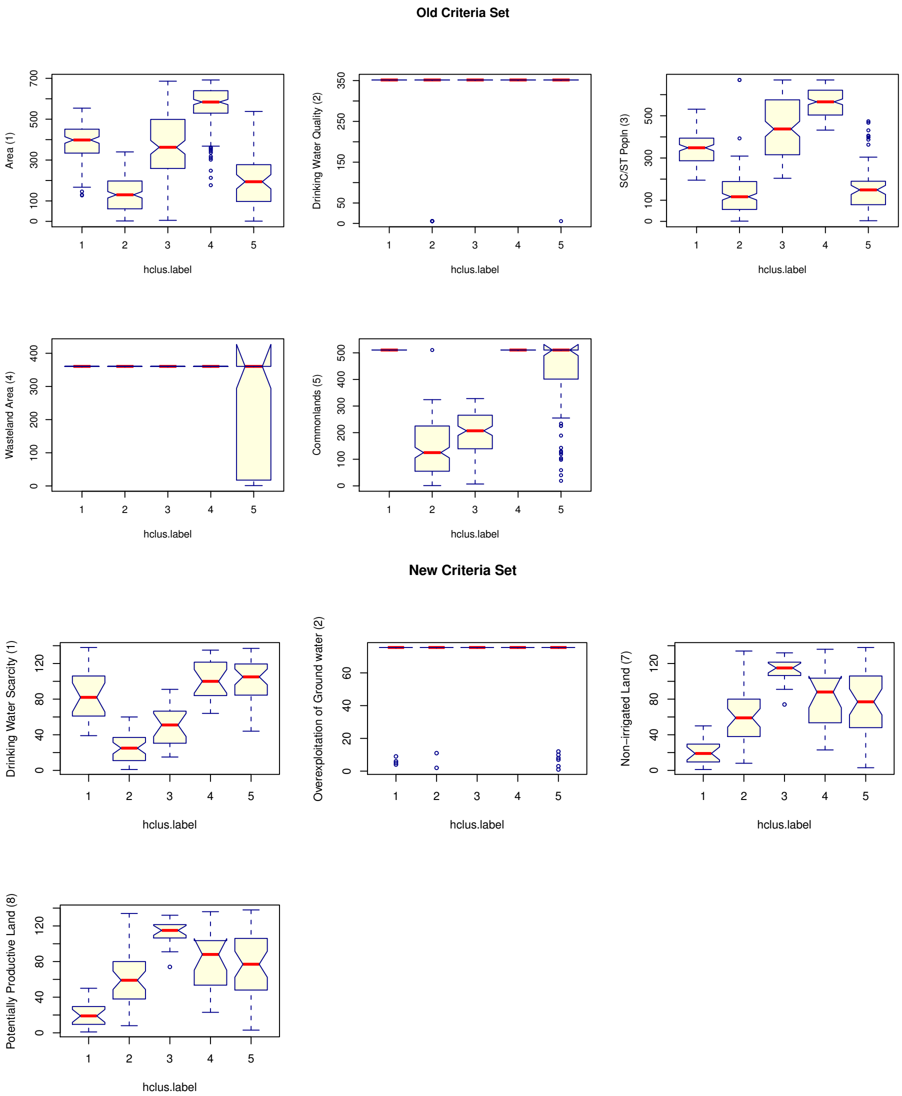


Fig. 6: Boxplots of ranked hierarchical clusters of the two criteria sets.

number of variables. We therefore selected the top five clusters and used box and whisker plots to explore which variables were most representative of those clusters (Fig. 6). The five clusters emerging from the old criteria set had the following properties: high in non-potable water, high in wasteland and high in common land. Four clusters emerged from the new criteria set with the only discernible property of over-exploitation of ground water. A test of autocorrelation of the clusters showed that both the group as well as all five individual clusters were highly clumped for the old criteria set while in the case of the new criteria set, the group and four of the five individual clusters were highly clumped (Tab. 8).

Table 8: Geary's test for spatial dependence on hierarchical cluster data. A high degree of spatial auto-correlation is exhibited by all sub-criteria barring cluster 4 in the new criteria set.

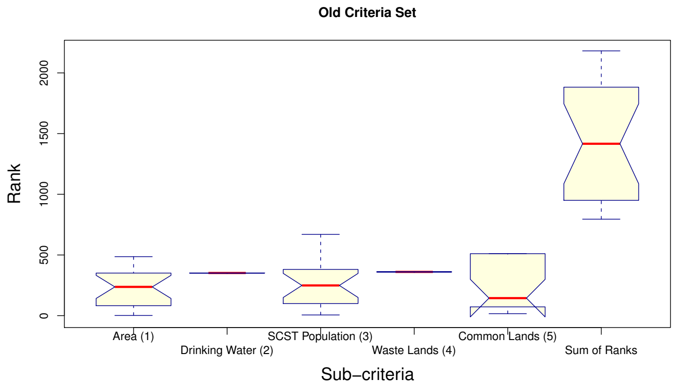
Old Criteria Set (1994 to 2008)			New Criteria Set (2008 onwards)		
	Geary C statistic	p-value		Geary C statistic	p-value
All clusters	0.8761	9.796e-07	All clusters	0.4760	< 2.2e-16
Index 1	0.9281	0.004579	Index 1	0.7601	2.12e-05
Index 2	0.9416	0.01330	Index 2	0.7046	6.51e-07
Index 3	0.8423	6.039e-09	Index 3	0.5339	4.898e-16
Index 4	0.9366	0.008016	Index 4	0.9013	0.0514
Index 5	0.3159	< 2.2e-16	Index 5	0.6229	1.435e-09

3.5 Comparing the top ranked watersheds across the sub-criteria

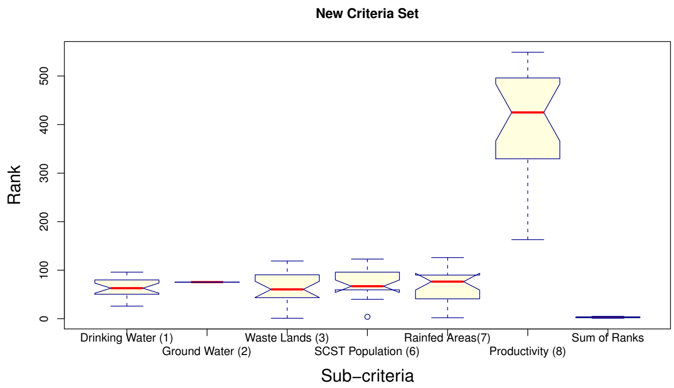
We then asked ourselves how different the top ranked micro-watersheds (sum of all sub-criteria) were from each of the sub-criteria. This was done by sorting the sum of the top twenty criteria in ascending order and visualising the results on a box plot (Fig. 7). Results clearly showed that the ranks were significantly different from all the other sub-criteria in both criteria sets. For the old criteria set they were furthest from sub-criteria 5 (availability of common lands) and closest to criteria 2 (shortage of drinking water). In the new criteria set they were furthest from sub-criteria 1 (drinking water scarcity) and closest to sub-criteria 8 (productivity potential of the land). The sub-division of micro-watersheds by revenue boundaries in the older criteria set also led to differences in the summed ranks of the old and new criteria sets even through some of the sub-criteria were identical.

In summary, our results showed that:

1. The criteria were spatially clumped for all sub-criteria except drinking water (sub-criteria 2) in the old criteria set and drinking water (sub-criteria 1) and productivity potential (sub-criteria 8) in the new criteria set.
2. Principal component analysis showed that three of the old and three of the new sub-criteria explained over 50% of the variation in the data. Mapping of the principal component data showed that the lower order principle components were single item components that identified the same areas.
3. A hierarchical cluster analysis showed there were statistically relevant clusters of the watershed across the criteria. A test of spatial auto-correlation among clusters showed that there was highly significant clumping as a group.
4. Single sub-criteria were usually highly auto-correlated. However when compared against other criteria from the same guidelines (using the Mantel test) they were negatively correlated or not significantly correlated. Thus the sub-criteria in both the criteria set contradicted each other.
5. When the ranks of the two different sets of criteria were summed the resulting maps were spatially distinct. That is to say that the old and new criteria sets would have resulted in the selection of different watershed areas for treatment.



(a) Old Criteria Set



(b) New Criteria Set

Fig. 7: Relative ranking of the top twenty micro-watersheds against the different sub-criteria in each criteria set..

4 Discussion and conclusion

Institutional organisation of watershed development programmes has taken priority over hydrological and landscape processes. This is leading to mistakes in prioritising micro-watersheds for restoration. Present priorities reflect the rural development focus and the belief in community based interventions, albeit that studies have found serious issues of equity in benefits accruing from these programmes (Hope, 2007; Kerr, 2002). The swing away from purely technical criteria, seems to have been spurred by a poor performance of projects prior to the common guidelines (Government of India, 2002). It is telling that the majority of scientific publications dealing with prioritisation of watersheds use a totally different set of criteria than those proposed by the common guidelines. It is therefore pertinent to ask whether the guidelines swung too far away from technicalities of watershed restoration? Kerr (2007) for instance, suggests that there are fundamental contradictions between implementing a watershed management project versus addressing hydrological problems which require operation at much larger scales. The evaluation of impacts of these projects is made more difficult due to lack of a baseline for measuring impacts of physical interventions (Patil et al, 2008; Calder et al, 2007b,a; Gosain and Rao, 2004) and methodological challenges in measuring impacts of social interventions (Hope, 2007).

The criteria for selection of watersheds in India is clearly an uncomfortable fit of social priorities into a watershed framework. For instance, the old criteria set, operational for nearly 15 years, was based on watersheds defined not by hydrological principals but by revenue village boundaries. The distribution of the areas of the resulting sub-divisions is highly skewed towards smaller units with the majority being within 50 hectares rendering them useless for restoration from a hydrological viewpoint. The new criteria-set however does away with this procedure which resulted in watershed divisions corresponding to their natural boundaries.

Watershed restoration in areas with high percentage of scheduled castes and tribes is no guarantee that the benefits will accrue to the target populations. Often times, the water resources and usufructs from the restored areas are dedicated to high caste families, temples, or other communities based on centuries old resource sharing agreements (Netting, 1993; Gadgil and Guha, 1992) . It is well documented that ecological goods and services constitute a substantial component of incomes for poor communities (World Resources Institute, 2005; Jodha, 1995). However prioritising areas for restoration based on higher population of these communities (sub-criteria 3 and sub-criteria 6 in the old and new criteria set respectively) implicitly assumes the availability and accessibility of common lands to this social group. This criteria assumes that resources are uniformly available to these social groups as long as they are within the same revenue village boundary. In much of India, access to natural resources is based on more than just the distance of the resource from habitations. Caste and political affiliations often limit access to high value resources, particularly to scheduled castes and tribal communities.

Coding the criteria sets into a GIS to prioritise areas for restoration merely resulted in prioritisation of disjointed regions of the watershed (Fig. 8). Spatial analysis of the ranked watersheds clearly showed that selection on the basis of any one set of criteria would automatically exclude other criteria as they are independently clumped. This leaves the practitioner few options than to choose restoration areas based on convenience. Thus the guidelines, albeit based on expert opinion, lead to ad hoc choices. Furthermore shifting between the old and new criteria set leads to even greater confusion as they choose a different set of micro-watersheds.

Given there are hundreds of programmes implemented under these guidelines, it is important to adopt a more scientific framework which can be used for decision support. Our work leads us to two major conclusions. First, the sub-criteria used to prioritise areas for treatment need to be re-articulated so they separate the restoration of watersheds from rural development. The planner will then be in a position to treat watersheds so they result in better hydraulic function and thus larger and more sustainable goods and services. There are two approaches which could work. The planner may use the rural development criteria either at a broad scale. For example, districts and blocks with high incidence of poverty, high densities of socially and economically disadvantaged groups may be selected. Micro-watersheds from within these regions may then be selected using hydrological criteria. A second approach would be to first select the top ranking micro-watersheds using the hydrological framework and then choose those with high ranks for social criteria from within them.

Our second conclusion is that the criteria need to be re-formulated so they conform to availability of data and tools that assist in their spatial and quantitative analysis. For instance,

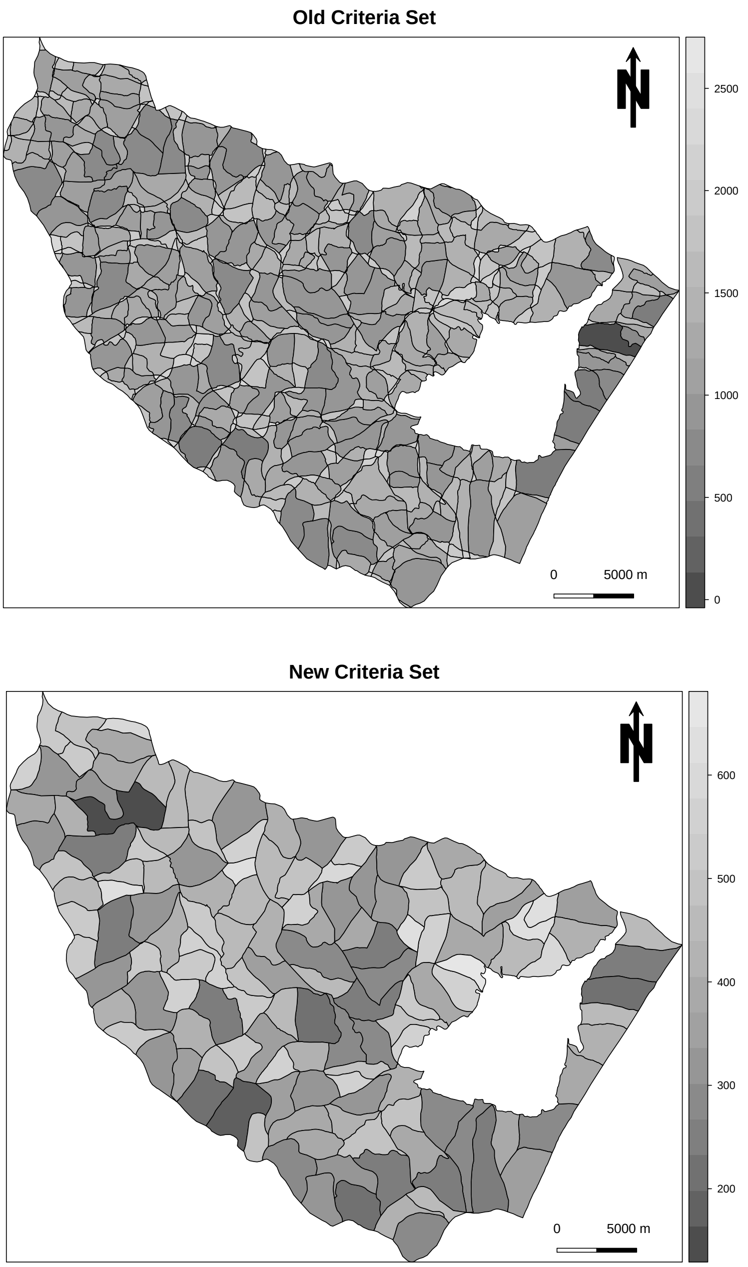


Fig. 8: Cumulative ranking for the two criteria sets. Darker the colour, higher the rank.

census and revenue records could provide the baselines for rural development criteria while landuse, slopes/elevation, soil types, hydrogeology and precipitation could provide the basis for the hydraulic criteria. Each of these "layers" are available from government or other public sources and conform to specific information needed to plan a rural development or watershed restoration programme.

Coarseness of data is known to affect results when employed to model hydrological processes (Baker et al, 2007). In our case, ranks of micro-watersheds could have been affected leading to different outcomes in the ranking. However this is an inherent limitation of watershed planning with disparate data. The lack of metadata and cartographic standards is another gap that needs to be addressed. Policy makers would do well to consult professional cartographers in the production of official datasets.

Our results are based on the analysis of a single watershed. It would be interesting to see whether similar patterns emerge in other areas. Another interesting line of comparison would be to evolve a new set of selection criteria based entirely on hydro-geological characteristics as done by various authors, or entirely on social basis, and to test them using a similar procedure. Regardless of the choice, our approach could help the guideline making process as it automates the analysis and works off publicly available datasets. Given that the outputs of the script are both graphical and provide a range of statistical analysis, experts can easily get feedback in the form of maps which shows the spatial distributions and the statistical relationships between the criteria.

Acknowledgements We'd like to acknowledge the inputs of Dr.Jagdish Krishnaswamy and Dr.Rauf Ali in the analysis and Mr.Srinivas V for some of the datasets used. We also thank the two anonymous reviewers for their detailed comments which greatly helped improve the quality of the manuscript. This study is part of project funded by the Natural Resources Data Management System, Department of Science and Technology, Government of India (grant no. NRDMS/11/1171/06).

References

Baker ME, Weller DE, Jordan TE (2007) Effects of stream map resolution on measures of riparian buffer distribution and nutrient retention potential. Landscape Ecology 22(7):973–992

Behera S, Panda RK (2006) Evaluation of management alternatives for an agricultural watershed in a sub-humid subtropical region using a physical process based model. Agriculture, Ecosystems and Environment 113(3):62–72, DOI 10.1016/j.agee.2005.08.032, URL www.elsevier.com/locate/agee

Bhandari PM, Bhadwal S, Kelkar U (2007) Examining adaptation and mitigation opportunities in the context of the integrated watershed management programme of the government of india. Mitigation and Adaptation Strategies for Global Change 12(5):919–933, DOI 10.1007/s11027-007-9106-5, URL http://dx.doi.org/10.1007/s11027-007-9106-5

Bhattacharyya P, Bhatt V, M D, al (2008) Soil loss tolerance limits for planning of soil conservation measures in Shivalik-Himalayan region of india. CATENA 73(1):117–124, DOI 10.1016/j.catena.2007.10.001

Bivand R, with contributions by Luc Anselin, Berke O, Bernat A, Carvalho M, Chun Y, Dormann C, Dray S, Halbersma R, Lewin-Koh N, Ma J, Millo G, Mueller W, Ono H, Peres-Neto P, Reder M, Tiefelsdorf M, , Yu D (2008) spdep: Spatial dependence: weighting schemes, statistics and models. R package version 0.4-24

Calder I, Gosain A, Rao M, Batchelor C, Snehalatha M, Bishop E (2007a) Watershed development in india. 1. biophysical and societal impacts. Environment, Development and

Sustainability DOI 10.1007/s10668-006-9079-7, URL http://dx.doi.org/10.1007/s10668-006-9079-7

Calder I, Gosain A, Rao MSRM, Batchelor C, Garratt J, Bishop E (2007b) Watershed development in india. 2. new approaches for managing externalities and meeting sustainability requirements. Environment, Development and Sustainability DOI 10.1007/s10668-006-9073-0, URL http://dx.doi.org/10.1007/s10668-006-9073-0

Chaplot V, Darboux F, Bourennane H, Legu\'edois S, Silvera N, Phachomphon K (2006) Accuracy of interpolation techniques for the derivation of digital elevation models in relation to landform types and data density. Geomorphology 77(1-2):126–141, DOI 10.1016/j.geomorph.2005.12.010

Cressie NAC (1993) Statistics for spatial data. Wiley series in probability and mathematical statistics, Wiley, New York

Dabral P, Baithuri N, Pandey A (2008) Soil erosion assessment in a hilly catchment of north eastern india using USLE, GIS and remote sensing. Water Resources Management 22(12):1783–1798, DOI 10.1007/s11269-008-9253-9, URL http://dx.doi.org/10.1007/s11269-008-9253-9

Deshpande RS (2008) Watersheds: Putting the cart before the horse. Economic & Political Weekly 43(06):74–76

Falissard B (2009) psy: Various procedures used in psychometry. URL http://CRAN.R-project.org/package=psy, r package version 1.0

Fox J (2009) polycor: Polychoric and Polyserial Correlations. R package version 0.7-7

Fox J, with contributions from Michael Ash, Boye T, Calza S, Chang A, Grosjean P, Heiberger R, Kerns GJ, Lancelot R, Lesnoff M, Messad S, Maechler M, Murdoch D, Neuwirth E, Putler D, Ripley B, Ristic M, Wolf P (2008) Rcmdr : R Commander. URL http://socserv.socsci.mcmaster.ca/jfox/Misc/Rcmdr/, r package version 1.3-15

Gadgil M, Guha R (1992) This fissured land: an ecological history of India. Oxford University Press, New Delhi; ed., University of California Press, Berkeley and Los Angeles, 1993

Gosain AK, Rao S (2004) GIS-based technologies for watershed management. Current Science 87(7):948–953

Goslee SC, Urban DL (2007) The ecodist package for dissimilarity-based analysis of ecological data. Journal of Statistical Software 22(7):1–19

Government of India (1994) Guidelines for watershed development programme. Tech. rep., Department of Land Resources, Ministry of Rural Development, Government of India, URL http://dolr.nic.in/Guideline.htm

Government of India (2001a) Census of india 2001. Tech. rep., Office of the Registrar General and Census Commissioner

Government of India (2001b) Guidelines for watershed development (Revised - 2001). Tech. rep., Department of Land Resources, Ministry of Rural Development, Government of India, URL http://dolr.nic.in/GuideWD.htm

Government of India (2002) 10th five year plan 2002-2007. Tech. rep., Planning Commission, Government of India, New Delhi

Government of India (2003) Guidelines for hariyali. Tech. rep., Department of Land Resources, Ministry of Rural Development, Government of India, URL http://dolr.nic.in/HariyaliGuidelines.htm

Government of India (2006) From hariyali to neeranchal: Technical committee on watershed programmes in india. Tech. rep., Department of Land Resources, Ministry of Rural Development, Government of India, URL http://dolr.nic.in/ParthaCommittee/ParthaCommitteeReport.htm

Government of India (2007) Conservation of wetlands in india: A profile. Tech. rep., Conservation Division-II, Ministry of Environment & Forests, Government of India New Delhi

Government of India (2008a) Annual report 2007-2008. Tech. rep., Ministry of Rural Development, Government of India, URL http://www.rural.nic.in

Government of India (2008b) Common guidelines for watershed development projects. Tech. rep., Department of Land Resources, Ministry of Rural Development, Government of India, URL http://dolr.nic.in/Guideline.htm

GRASS Development Team (2008) The Geographic Resources Analysis and Support System (GRASS). ITC-irst, Trento, Italy., URL http://grass.itc.it

Hajkowicz S, Collins K (2007) A review of multiple criteria analysis for water resource planning and management. Water Resources Management 21(9):1553–1566, DOI 10.1007/s11269-006-9112-5, URL http://dx.doi.org/10.1007/s11269-006-9112-5

Hajkowicz SA, McDonald GT, Smith PN (2000) An evaluation of multiple objective decision support weighting techniques in natural resource management. Journal of Environmental Planning and Management 43(4):505, DOI 10.1080/713676575, URL http://www.informaworld.com/10.1080/713676575

Harrell Jr FE (2009) Hmisc: Harrell Miscellaneous. URL http://CRAN.R-project.org/package=Hmisc, with contributions from many other users. R package version 3.7-0

Hope RA (2007) Evaluating social impacts of watershed development in india. World Development 35(8):1436–1449, DOI 10.1016/j.worlddev.2007.04.006, URL www.elsevier.com/locate/worlddev

Jodha NS (1995) Common property forest resource management - common property resources and dynamics of rural poverty in india's dry regions. Unasylva 46, URL http://www.fao.org/docrep/v3960e/v3960e05.htm

Kerr J (2002) Watershed development, environmental services, and poverty alleviation in india. Water Res 30(8):1387–1400, URL www.elsevier.com/locate/worlddev

Kerr J (2007) Watershed management: Lessons from common property theory. International Journal of the Commons 1(1):89–109

Kerr J, Pangare G, Pangare VL (2002) Watershed development projects in india. Research Report 127, International Food Policy Research Institute, Washington D.C., URL http://www.ifpri.org

Kerr J, Milne G, Chhotray V, Baumann P, James A (2007) Managing watershed externalities in india: Theory and practice. Environment, Development and Sustainability 9(3):263–281, DOI 10.1007/s10668-005-9022-3, URL http://dx.doi.org/10.1007/s10668-005-9022-3

de Kok J, Kofalk S, Berlekamp J, Hahn B, Wind H (2009) From design to application of a decision-support system for integrated river-basin management. Water Resources Management 23(9):1781–1811, DOI 10.1007/s11269-008-9352-7, URL http://dx.doi.org/10.1007/s11269-008-9352-7

Lee S, Poon W (1987) Maximum likelihood estimation of multiple correlations and canonical correlations with categorical data. Applied Psychological Measurement 11(3):317–323, URL http://apm.sagepub.com/cgi/content/abstract/11/3/317

Mishra A, Kar S, Singh VP (2007a) Prioritizing structural management by quantifying the effect of land use and land cover on watershed runoff and sediment yield. Water Resource Management 21:1899–1913, DOI 10.1007/s11269-006-9136-x

Mishra SK, Pandey RP, Jain MK, Singh VP (2007b) A rain duration and modified AMC-dependent SCS-CN procedure for long duration rainfall-runoff events. Water Resour Manage pp 77,843–72,117, DOI 10.1007/s11269-007-9196-6

Moreno-Mateos D, Mander \, Pedrocchi C (2010) Optimal location of created and restored wetlands in mediterranean agricultural catchments. Water Resources Management DOI 10.1007/s11269-009-9564-5, URL http://www.springerlink.com/index/10.1007/s11269-009-9564-5

Myers WL, Evans BM, Andeson MC (1996) Spatial inconsistency of watershed delineations among agencies and scales in pennsylvania. In: Spatial Accuracy Assessment in Natural Resources and Environmental Sciences: Second International Symposium, Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, CO: U.S, vol General Technical Report RM-GTR-277, pp 561–567

Netting RM (1993) Smallholders, householders: Farm families and the ecology of intensive, sustainable agriculture. Stanford Univ Press

Nordhausen K, Sirkia S, Oja H, Tyler DE (2010) ICSNP: Tools for Multivariate Nonparametrics. URL http://CRAN.R-project.org/package=ICSNP, r package version 1.0-7

Openshaw S (1984) The modifiable areal unit problem: Concepts and techniques in modern geography 38. Norwich: Geo books

Ostrom E (1990) Governing the commons : the evolution of institutions for collective action. The Political economy of institutions and decisions, Cambridge University Press, Cambridge; New York

Pandey A (2007) Runoff and sediment yield modeling from a small agricultural watershed in india using the WEPP model. Journal of Hydrology pp 86–80, DOI 10.1016/j.jhydrol.2007.10.010, URL www.sciencedirect.com

Patil J, Sarangi A, Singh O, Singh A, Ahmad T (2008) Development of a GIS interface for estimation of runoff from watersheds. Water Resources Management 22(9):1221–1239, DOI 10.1007/s11269-007-9222-8, URL http://dx.doi.org/10.1007/s11269-007-9222-8

Pebesma EJ, Bivand RS (2005) Classes and methods for spatial data in r. R News 5(2):9–13, URL http://CRAN.R-project.org/doc/Rnews/

Periasamy (2010) Revenue department policy note 2010-2011. Policy Note 41, 51, Minister for Revenue and Housing, Government of Tamil Nadu, URL http://www.tn.gov.in/policynotes/pdf/revenue.pdf

Pernetta JC (1993) Marine protected area needs in the south asian seas region. volume 2: India. A marine conservation and development report., IUCN, Gland, Switzerland.

R Development Core Team (2008) R: A Language and Environment for Statistical Computing. Vienna, Austria, URL http://www.R-project.org, ISBN 3-900051-07-0

Reddy VR (2006) Getting the implementation right. Economic & Political Weekly 41(40):4292–4295

Rossini AJ, Heiberger RM, Sparapani RA, Machler M, Hornik K (2004) Emacs speaks statistics: A multiplatform, multipackage development environment for statistical analysis. Journal of Computational and Graphical Statistics 13(1):247–261

Sabatier PA, Pelkey N (1987) Incorporating multiple actors and guidance instruments into models of regulatory policymaking: An advocacy coalition framework. Administration Society 19(2):236–263, DOI 10.1177/009539978701900205, URL http://aas.sagepub.com/cgi/content/abstract/19/2/236

Shapiro M (2006) v.surf.idw. URL http://grass.osgeo.org/

Swift A, Liu L, Uber J (2008) Reducing MAUP bias of correlation statistics between water quality and GI illness. Computers, Environment and Urban Systems 32(2):134–148

The Postgresql Development Group (2007) Postgresql. URL http://www.postgresql.org, version 8.1

Tripathi MP, Panda RK, Raghuwanshi NS (2003) Identification and prioritisation of critical sub-watersheds for soil conservation management using the SWAT model. Biosystems Engineering 85(3):365–379

Vaidyanathan A (2006) Restructuring watershed development programmes. Economic & Political Weekly 41(27/28):2984–2987

Venables WN, Ripley BD, Chambers J, Eddy W, H\"ardle W, Sheather S, Tierney L (2000) S programming, 4th edn. Statistics and Computing, Springer Science+Business Media, New York

World Resources Institute (2005) World resources 2005: The wealth of the poor - managing ecosystems to fight poverty. Tech. rep., World Resources Institute (WRI) in collaboration with United Nations Development Programme, United Nations Environment Programme and World Bank, Washington, DC, ISBN 1-56973-582-4