Automated estimation and analyses of meteorological drought characteristics from monthly rainfall data

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Abstract

The paper describes a new software package for automated estimation, display and analyses of various drought indices – continuous functions of precipitation that allow quantitative assessment of meteorological drought events to be made. The software at present allows up to five different drought indices to be estimated. They include the Decile Index (DI), the Effective Drought Index (EDI), the Standardized Precipitation Index (SPI) and deviations from the long-term mean and median value. Each index can be estimated from point and spatially averaged rainfall data and a number of options are provided for months' selection and the type of the analysis, including a running mean, single value or multiple annual values. The software also allows spell/run analysis to be performed and maps of a specific index to be constructed. The software forms part of the comprehensive computer package, developed earlier and designed to perform the multitude of water resources analyses and hydro-meteorological data processing. The 7-step procedure of setting up and running a typical drought assessment application is described in detail. The examples of applications are given primarily in the specific context of South Asia where the software has been used.

Software availability

Package:
    The SPATSIM software package;
Availability:
    From the Institute for Water Research (IWR) at Rhodes University;
Cost:
    No development cost involved, the Institute is obliged to pass on the application development license costs charged by ESRI. This amounts to approximately 200 USD;
Description:
    Available on IWR website http://www.ru.ac.za/institutes/iwr/. Updates to the software are regularly posted on the IWR website and readily downloaded at no cost by registered users

1. Introduction

Meteorological droughts are temporary, recurring natural disasters, which originate from the lack of precipitation and can bring significant economic losses. It is not possible to avoid meteorological droughts, but they can be predicted and monitored, and their adverse impacts can be alleviated. The success of the above depends, amongst the others, on how well the droughts are defined and drought characteristics quantified. Quantitative drought definitions identify the beginning, end, spatial extent and severity of a drought. They are often region-specific and are based on scientific reasoning, which follows the analysis of certain amounts of hydro-meteorological information. Quantitative definitions of a drought are formulated in terms of *drought indices*.

Drought indices are normally continuous functions of rainfall and/or temperature, river discharge or other measurable hydrometeorological variable. A large number of drought indices have been suggested to date, including Palmer Drought Severity Index (PDSI – Palmer, 1965), Crop Moisture Index (CMI – Palmer, 1968), Standardized Precipitation Index (SPI – McKee et al., 1993), "Deciles" (Gibbs and Maher, 1967), FAO water satisfaction index (Frere and Popov, 1979), Agro-hydro Potential (AHP – Petrasovits, 1990), Index of Moisture Adequacy (IMA – Sastri, 1993), Surface Water Supply Index (SWSI – Shafer and Dezman, 1982), and multiple indices of low river flow (Smakhtin, 2001). Some of these indices focus on the degree to which crop moisture requirements are met (e.g. CMI, AHP, IMA above), others intend to assess the lack of overall water availability in a region or a river basin (SWSI above). Yet others are flexible enough to identify, assess and monitor drought progress over the range of temporal scales and therefore evaluate different types of water shortages (SPI above).

Reviews of drought indices may be found in many sources, including (http://www.drought.unl.edu/whatis/indices.htm, Tate et al., 2000 and Smakhtin and Hughes, 2004).

The inherent complexity of drought phenomena implies that no drought index is ideal for all regions or tasks. In most cases, it is useful and necessary to consider more than one index, examine the sensitivity and accuracy of indices, the correlation between them and explore how well they compliment each other in the context of a specific research or management objective (Guttman, 1998, Wu et al., 2001 and Morid et al., 2006). Many computer programs and on-line tools were developed to estimate either individual indices separately, or several indices at once (e.g. Wu et al., 2001 and Rossi and Cancelliere, 2003; http://www.drought.unl.edu/whatis/indices.htm; National Agricultural Decision Support System (NADSS) http://nadss.unl.edu). Consequently, the need to simply calculate various drought indices is not, on its own, sufficient justification for a new software development. It is, however, important to ensure that drought is seen as a comprehensive water resources issue and is assessed within a comprehensive water resources software environment. Facilities should exist to import information from multiple raw data formats, display and analyze various drought indices in a variety of ways, convert point rainfalls and drought indices to representative areal values, perform rapid spatial analysis of different drought characteristics and link to various hydrological, ecological and water resources models to analyze different components of droughts and to interpret their outputs. The automation of these procedures could facilitate data intensive, regional drought analyses (e.g. Lloyd-Hughes and Saunders, 2002).

Considering the number and magnitude of the requirements listed above, it is logical to consider incorporating drought estimation and analyses routines into an existing software package, which already has some of the required features, is flexible enough to work efficiently with large data sets, is cost effective and is continuously developing to include more components relevant to drought analyses. This paper describes the incorporation of several drought assessment modules into one such package designed to cover a much wider range of water resources applications. The paper describes the general features of this package followed by a description of several selected drought indices and the steps necessary to set up, run and examine the results of a typical drought analysis application.

2. General features of the SPATSIM software package

The SPATSIM (*SP*atial and *T*ime *S*eries *I*nformation *M*odeling) software package has been under development at the Institute for Water Research (IWR) of Rhodes University, South Africa since 1999 (Hughes and Forsyth, in press). It is a relatively new software product which is quickly gaining recognition in South Africa and other countries. It has been applied extensively in southern Africa (South Africa, Zimbabwe, Zambia, Tanzania, Swaziland and Angola) for various water resource analysis studies including environmental flow assessments and hydrological model based water resource determinations.

The package has been developed in Delphi using ESRI Map Objects as a tool for managing and modeling the data that are typically associated with water resource assessment studies. It contains an integrated database management system that uses GIS shape files as the main form of data access. It has a number of built-in data analysis and processing tools, such as for generating catchment average rainfall data from gauged station data or generating monthly and annual frequency tables from time series data. It also includes a wide range of external models that can be setup and integrated seamlessly with the database, i.e. the models access their data requirements from the SPATSIM database and store their results in the database without any intermediate data transformation. The models include spatial interpolation of observed flow records (Hughes and Smakhtin, 1996), monthly rainfall–runoff simulation (Hughes, 2004) and a desktop model for environmental flow assessment (Hughes and Münster, 2000). SPATSIM has a comprehensive set of Help facilities, and all new users can consult 'Help' to obtain a basic understanding of the system and how to make use of the various menu items. A detailed description of SPATSIM can be found on the IWR website (http://www.ru.ac.za/institutes/iwr – see the link to Hydrological Models and Software), as well as in Hughes and Forsyth (in press).

SPATSIM's flexible environment provided an excellent opportunity to incorporate drought assessment or management routines. Considering that such analyses are carried out by many centres and individuals throughout the world, the drought assessment routines should:

• ensure that existing data import facilities are satisfactory for a variety of drought assessment projects (and associated data formats) and cater for the requirements of various future users;

• have facilities for generating time series of drought indices from station rainfall data and from areal rainfall data interpolated from station (i.e. point) rainfall data;

• provide a range of facilities for further display and regional analysis of drought indices;

• provide clear in-built documentation of all drought indices and drought–related facilities in the SPATSIM 'Help' system.

3. Drought indices currently included in SPATSIM

The software package currently includes five drought indices: the Standardized Precipitation Index (SPI), the Decile Index (DI, or "deciles"), the Effective Drought Index (EDI) and the departures from the long-term mean and median precipitation values. The commonality between all these indices is that they are calculated exclusively on the basis of *monthly rainfall data*. Rainfall data are widely used to calculate drought indices, because long-term rainfall records are more readily available than other types of hydrological or climatic data. While rainfall data alone may not reflect the spectrum of drought related conditions, they can serve as a pragmatic solution in data-poor regions and as a useful point of departure in drought software development. Although the indices are normally referred to here and elsewhere as "drought indices", all of them can effectively be used for the assessment of both dry and wet conditions. A brief description of the indices and their implementation in SPATSIM is given below. A potential user of the system, however, is advised to consult the original literature sources, explaining each and every drought index in more detail. This is a necessary pre-requisite for understanding the advantages and limitations of the indices, as well as of the modifications to the original algorithms, which have been introduced in SPATSIM

3.1. Standardized Precipitation Index (SPI)

The SPI index was developed by McKee et al. (1993). In its original version, a long-term precipitation record at a station is fitted to a probability (gamma) distribution, which is then transformed into a normal distribution so that the mean SPI is zero. The index values are therefore the standardized deviations of the transformed rainfall totals from the mean. The SPI may be computed with different time steps (1 month, 3 months, 24 months, etc.) to facilitate the assessment of the effects of a precipitation deficit on different water resources components (groundwater, reservoir storage, soil moisture, streamflow). Positive SPI values indicate greater than median precipitation and negative values indicate less than median precipitation. Drought periods are represented by relatively high negative deviations. Normally, the "drought" part of the SPI range is arbitrary split into moderately dry ($-1.0 > SPI > -1.49$), severely dry ($-1.5 > SPI > -1.99$) and extremely dry conditions ($SPI < -2.0$). A drought event starts when SPI value reaches −1.0 and ends when SPI becomes positive again (McKee et al., 1993). In the SPATSIM application, there are several options available for accumulating the monthly rainfall values into a time series before the SPI (or any other index) is calculated. These options are explained latter in the text. The time series is then normalized using an automated procedure to optimize the λ (lambda) parameter of the Box–Cox approximation for transformation to a normal distribution, using equations:

$$\begin{aligned} y &= (x^{\lambda} - 1)/\lambda \quad \text{for } \lambda \neq 0 \\ y &= \ln(x) \quad \text{for } \lambda = 0 \end{aligned} \qquad (1)$$

where x is the original variable (rainfall) and y is the transformed variable.

3.2. Deciles

In this method, originally suggested by Gibbs and Maher (1967), monthly precipitation totals from a long-term record are first ranked from highest to lowest to construct a cumulative frequency distribution. The distribution is then split into 10 parts (deciles). The first decile is the precipitation value not exceeded by the lowest 10% of all precipitation values in a record, the second is between the lowest 10 and 20%, etc. Any precipitation value (e.g.

from the current or past month) can be compared with and interpreted in terms of these deciles. Decile Indices (DI) are often grouped into five classes, two deciles per class. If precipitation falls into the lowest 20% (deciles 1 and 2), it is classified as “much below normal”. Deciles 3 and 4 (20–40%) indicate “below normal” precipitation, deciles 5 and 6 (40–60%) give “near normal” precipitation, deciles 7 and 8 (60–80%) “above normal” and deciles 9 and 10 (80–100%) are “much above normal”.

The original DIs are therefore integer numbers (1–5 or 1–10), while in SPATSIM, no attempt is made to convert the actual frequency (exceedence) values into DI groups. The time series of this drought index is therefore based on the same type of analysis as the original decile of Gibbs and Maher (1967), but is represented by actual frequency values in percent instead of decile integer numbers.

3.3. Effective Drought Index (EDI)

Unlike many other drought indices, the EDI in its original form (Byun and Wilhite, 1996) is calculated with a daily time step. However, its principles can be used similarly with monthly precipitation data as is done in SPATSIM and described below. The EDI is a function of precipitation needed for a return to normal conditions (PRN). PRN is precipitation, which is necessary for the recovery from the accumulated deficit since the beginning of a drought. PRN, in turn, effectively stems from monthly effective precipitation (EP) and its deviation from the mean for each month.

The first step is the calculation of EP, defined as a function of the current month's rainfall and weighted rainfall over a defined preceding period (selected by the duration option in SPATSIM, see below). If P_m is the rainfall m-1 months before the current month and N is the duration of preceding period then the EP for the current month is:

$$\mathrm{EP}=\sum_{m=1}^{N}\left[\left(\sum_{i=1}^{m}P_m\right)\Big/m\right] \qquad (2)$$

For example, if $N = 3$ then EP = $P_1 + (P_1 + P_2)/2 + (P_1 + P_2 + P_3)/3$, where P_1, P_2 and P_3 are precipitation values during the current month, previous month and 2 months before, respectively. The mean and standard deviations of the EP values for each month are then calculated and the time series of EP values is converted to deviations from the mean (DEP). PRN values are then calculated as:

$$\mathrm{PRN}=\mathrm{DEP}/\sum(1/N) \qquad (3)$$

The summation term is the sum of the reciprocals of all the months in the duration N (i.e. for $N = 3$ months, this term will be equal to: 1/1 + 1/2 + 1/3). Finally the EDI is calculated as:

$$\mathrm{EDI}=\mathrm{PRN}/\mathrm{Std}(\mathrm{PRN}) \qquad (4)$$

where Std (PRN) is the standard deviation of the relevant month's PRN values. In this algorithm, no normalization of the index or rainfall data is performed and therefore the skewness of the original time series is preserved. This means that positively skewed rainfall data can result in a larger range of positive EDI values than the range of negative EDI values. This is not, however, seen as a critical issue as the negative values are the important ones in that they represent the ‘rainfall’ that is required for a return to normal from a drought.

Similar to the SPI, the EDI values are standardized, which allows drought severity at two or more locations to be compared with each other regardless of climatic differences between them. The EDI also has thresholds indicating the range of wetness – from extremely dry to extremely wet conditions. The “drought range” of the EDI indicates extremely dry conditions at $\mathrm{EDI} < -2$, severe drought at $-1.5 > \mathrm{EDI} > -1.99$ and moderate drought at $-1.0 > \mathrm{EDI} > -1.49$. Near normal conditions are indicated by $-0.99 < \mathrm{EDI} < 0.99$.

3.4. Departure from the mean and median

These indices are simple by definition, easy to calculate and are easily understood by a general audience. They are also the variations of the “percent of normal”. “Normal” may be and usually is set to a long-term mean or median precipitation value. For example, meteorological drought in India is defined when rainfall in a month or a season is less than 75% of its long-term mean. If the rainfall is 50–74% of the mean, a moderate drought event is assumed to occur, and severe drought occurs when rainfall is less than 50% of its mean (e.g. Khan, 1998). Droughts in South Africa are defined as periods with less than 70% of normal precipitation. This becomes a severe drought when two consecutive seasons experience 70% of normal rainfall or less (Bruwer, 1990). There are many other similar indices and associated drought definitions (Tate et al., 2000). They are normally region-specific and explicitly set locally appropriate rainfall limits and durations of rainless periods for the definition of droughts of different extremes. In SPATSIM, the Departure from the Mean and Departure from the Median are simple measures of rainfall deviation (from mean or median for the selected period, respectively) and are neither normalized nor standardized.

4. Setting up a typical drought assessment application

4.1. Step 1: Organize SPATSIM features (spatial coverages)

SPATSIM uses spatial *features* (coverages) and temporal *attributes* (time series, Fig. 1). The assumption is that there will be at least two available coverages: one point coverage representing raingauge locations for raw monthly rainfall data and one polygon coverage representing administrative areas or catchments. If the latter is not available, the facility in SPATSIM can be used to establish a new polygon coverage of equal size grid squares. This can then be used to generate the areal rainfall data from the point rainfall and to display the spatial variation of drought indices

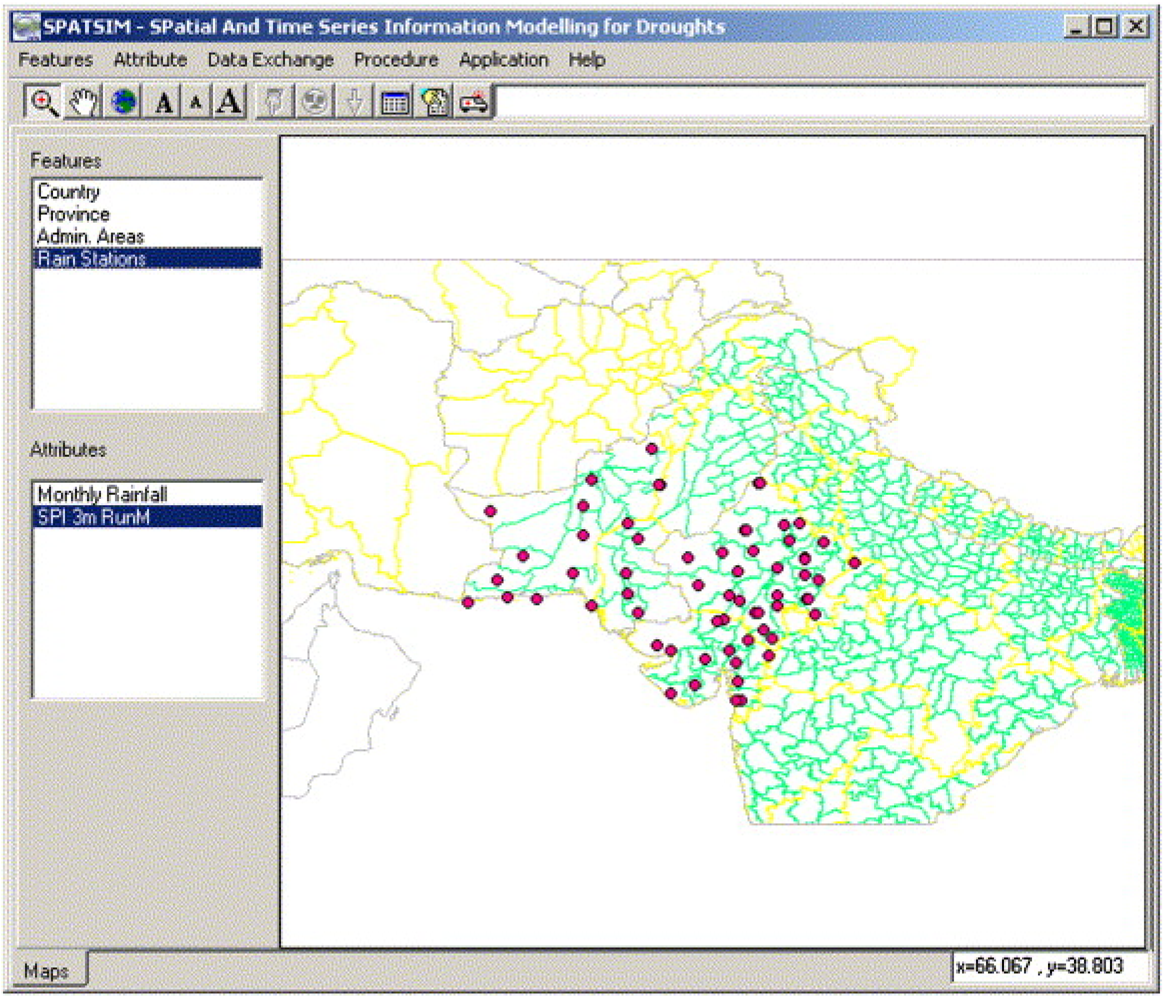

Fig. 1. The main SPATSIM screen, showing part of South Asia region, with the selection windows for available spatial features and attributes, associated with the highlighted feature.

4.2. Step 2: Create main SPATSIM attributes (time series)

It is necessary to design the SPATSIM attribute structure to store and manage the raw and processed data. This simply involves adding new attributes of different types and giving them suitable names that can be recognized later. For the raingauge point coverage, the minimum requirement will be a time series attribute that will be used to store the raw monthly rainfall data. For the polygon coverage that will be used for generating the spatially distributed drought indices, a wide range of attributes may be required depending on the analyses intended. At least a time series attribute will be needed that will be used to store the area average rainfall data interpolated from the point rainfall data.

Additional time series attributes will be required for each drought index that is to be generated and it is important to name these carefully so that they can be readily identified for future analysis purposes. Fig. 2 indicates that there is a wide variety of index values that can be generated (see step 5 for more details). Users could get confused trying to remember which drought index has been stored in which attribute. That is why it is essential to use recognizable names for the attributes. For example *'SPI Annual 3m Jan'* could be used for an SPI based on a single annual value with a 3-month duration starting in January. '*SPI 12m RunM*' might be used for an SPI value based on 12-month running means. The lower right hand box displays all the available attributes that have been established in an example application (Fig. 2). SPATSIM has a facility (the memo attributes), which can be used to provide a key to the information stored within other attributes.

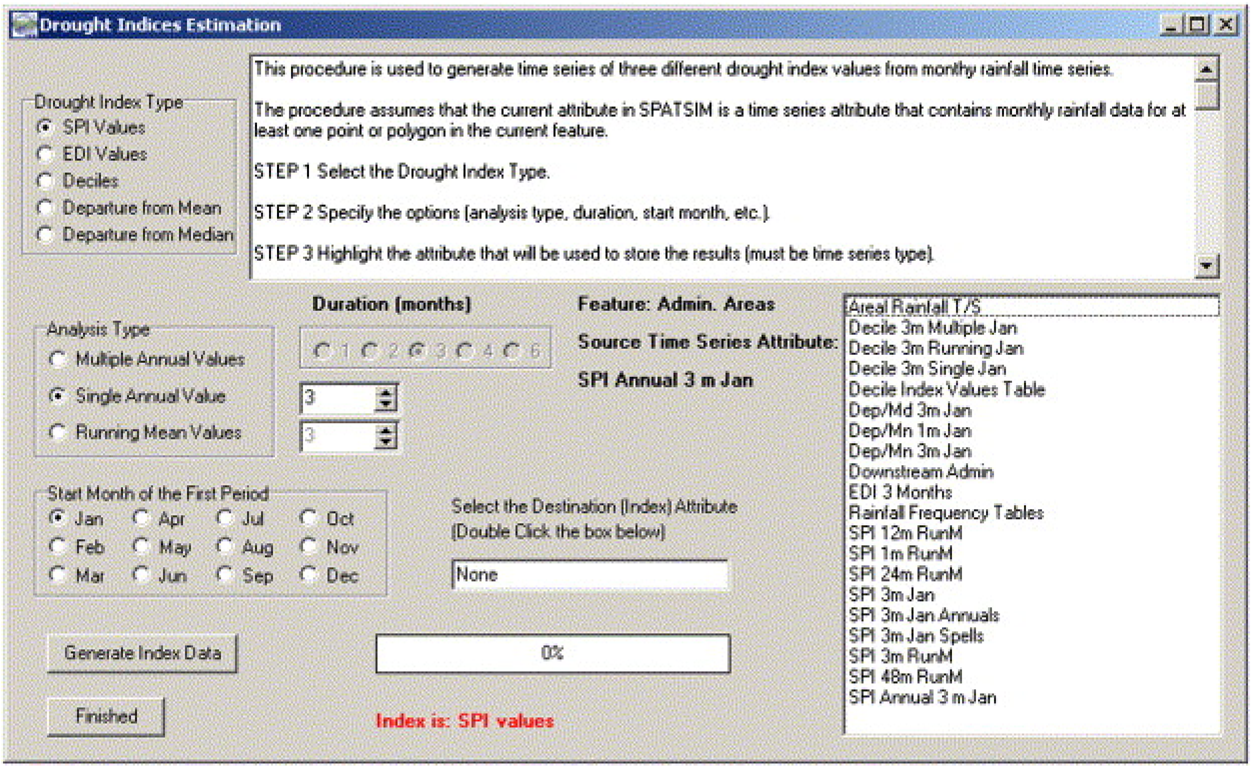

Fig. 2. Main drought index generation screen showing the various drought index options that are available, help window and example time series calculated (right window).

4.3. Step 3: Import raw rainfall data

A set of time series data import routines are available to load suitably formatted text files of monthly rainfall data to the SPATSIM time series attribute associated with the point raingauge feature. There are a wide variety of options available to ensure that various original formats can be imported. One common format is the 'spreadsheet' type: annual plus 12 monthly values per line in a text file with a defined number of explanation lines above the data – called the *header*. Another common format is the 'continuous data' type (the start date – e.g. day/month/year – followed by one data value per line). Common problems are related to the lack of line feeds and carriage return codes at the end of the text lines when exported from other specialist software. These can usually be solved by importing the data into a text editor and then simply saving the data. Bulk data imports can be achieved by naming the raw data text files with the same text as the spatial element (points) labels.

4.4. Step 4: Generate areal rainfall data

A procedure is provided to generate areal rainfall data for a polygon feature from point rainfall data. It uses the inverse distance squared interpolation method and data sets from rainfall stations located within a user-defined search radius. The procedure fills missing data and generates complete records for all the polygons to be used. The examples of polygons include catchments, administrative divisions or a rectangular grid. If the procedure cannot find a rainfall value for a particular month at any station within a defined search radius, mean monthly rainfall values for identified stations are used to calculate a polygon rainfall value for this month. This can be a problem if there are extended missing data periods within several raingauge time series in the same area. However, the problem is usually quite easy to recognize as a repeating pattern of rainfall will be seen in the areal rainfall time series viewed using the SPATSIM display facilities (see step 7). The user can visually compare and inspect the data series to ensure that the areal interpolation process has worked successfully. Other problems that can occur are related to an inappropriate search radius, insufficient raingauges in a particular area, or selection of too few (or too many) raingauges on which to base the interpolation.

4.5. Step 5: Generate drought indices

This procedure is used to generate time series of a range of drought indices from complete (no missing data) time series of monthly rainfall. The input data for the analysis will be the data associated with the currently selected attribute (a time series of rainfall) and feature.

A user can select from various options for different index types and ensure that the destination attribute selected for storing the data has an appropriate name to identify what data are being stored (see step 2). The user has the flexibility of choosing different durations, starting months and data integration types (Fig. 2). The analysis options and duration selections are disabled if they are not appropriate to a specific index that has been selected. Most indices can be calculated as multiple annual values, single annual value or running mean values. This step can be repeated for as many different index types as required.

The first option (multiple annual values) allows the starting month and durations of 1,2,3,4 or 6 to be selected. If January and 3 months duration is selected, the groups of months which will be analyzed are JFM, AMJ, JAS, OND (the capital letters here stand for the month: J – for January, F – for February, etc).

The second option (single annual value) allows the starting month and durations of 1–12 to be selected. In all cases, only 1 value per year is generated based on rainfall accumulated over the duration from the start month. For example, if January and 6 months are selected, the annual values will be based on rainfall accumulated for JFMAMJ (January–June), while the rainfall for the other months will be ignored.

The third option (running mean/total values) is similar to the first (multiple annual values), but 12 values per year are always generated regardless of the selected duration. The selected duration can be any value up to 48 months. If a duration of 6 months is selected and the rainfall data start in January 1960, the first index value will be based on rainfall accumulated for 1960 JFMAMJ, the second for 1960 FMAMJJ, the third for 1960 MAMJJA, etc. This procedure is similar to the original SPI calculation proposed by McKee et al. (1993).

4.6. Step 6: Generate summary drought index information

Generating summary information on drought indices is necessary if subsequent mapping of index values is required (step 7). Two types of drought index summary information can be generated, both at the same time (Fig. 3). The first option is a summary of actual index values. The second option is a summary of the run (or spell) characteristics of the index data (i.e. for how long a drought index *continuously* lies below and above a certain critical threshold).

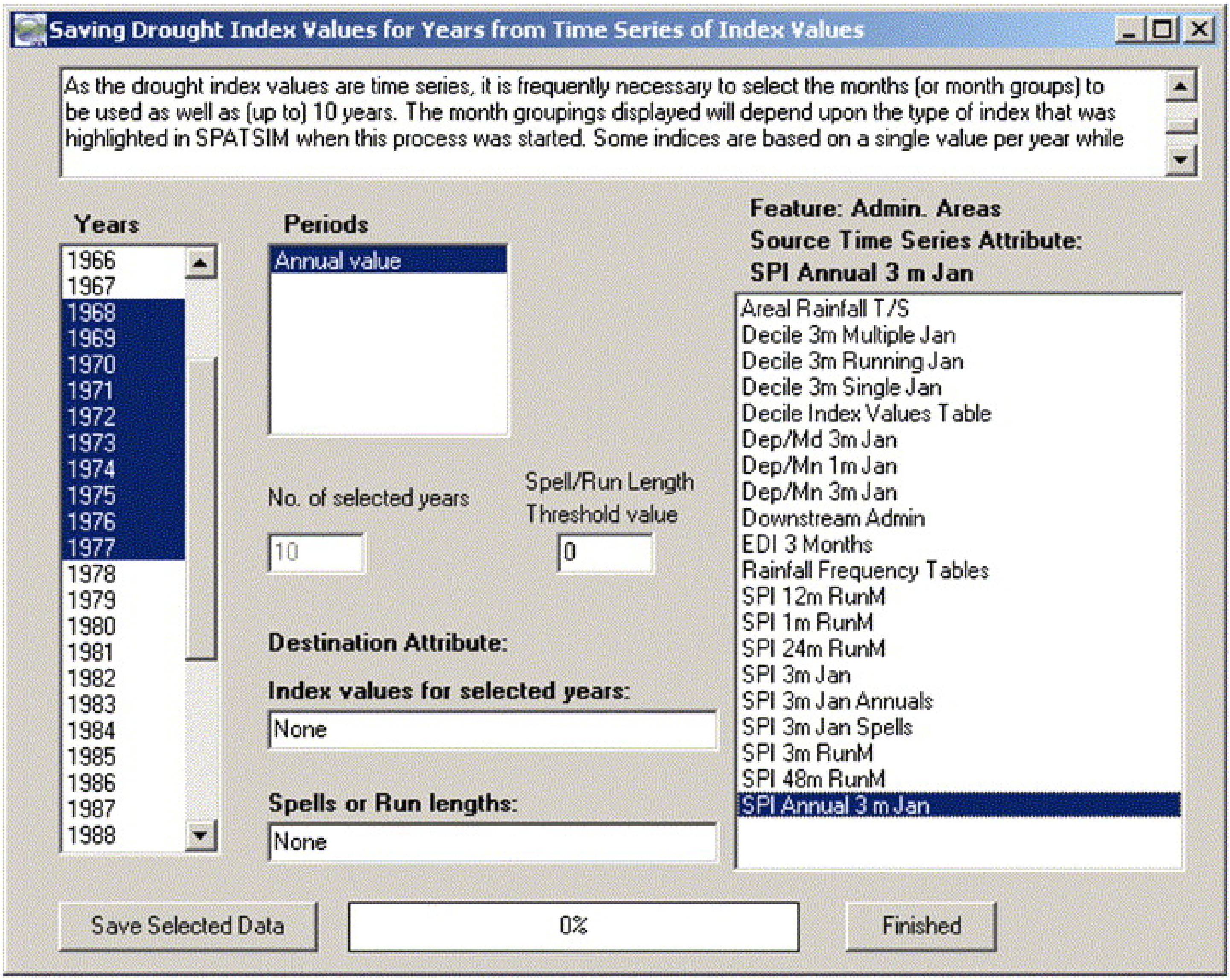

Fig. 3. A screen for saving drought index information to a summary table.

In both cases data are extracted for up to 10 sample years from a time series of drought index values and stored in a 2-D array type attribute (year, polygon). The summary data for many different drought indices could be stored and therefore the naming approach for the attributes within SPATSIM is very important. The choice of storing a sample of 10 values is quite arbitrary, but is based on the assumption that a larger number would be rather unnecessary and, if required, could be stored within more than one summary attribute. In certain cases (i.e. where there are multiple drought index values per year), it is necessary to select not only the years but also the month for the required drought index. While multiple years can be selected, multiple months cannot to avoid confusion (i.e. a user may select several years for the period JAS, but cannot select JFM, AMJ, JAS and OND for 1968). The same set of years but with a different month group may, however, be selected and stored.

The analysis is based on the time series attribute that is current at the time of running the procedure. This process can therefore be repeated as many times as necessary to store summary data for all the drought indices generated during step 5.

4.7. Step 7: Displaying drought index information

Two groups of display facilities are available in SPATSIM to visualize drought index information (or any water resources information and data). The first allows the generated time series of any drought index (step 5) to be displayed. The second allows polygon features to be classified and mapped using generated index summary information (step 6).

Drought index time series can be displayed and compared using the SPATSIM display facility (TSOFT) for a range of polygons (or different index types for the same polygon). In other words, it is possible to compare the same index for several areas, or display different index time series for the same area (Fig. 4). Within TSOFT, additional analysis facilities are available to assess the frequency or run/spell characteristics of the drought indices. The ‘Help’ system provides information about how to load time series data into TSOFT.

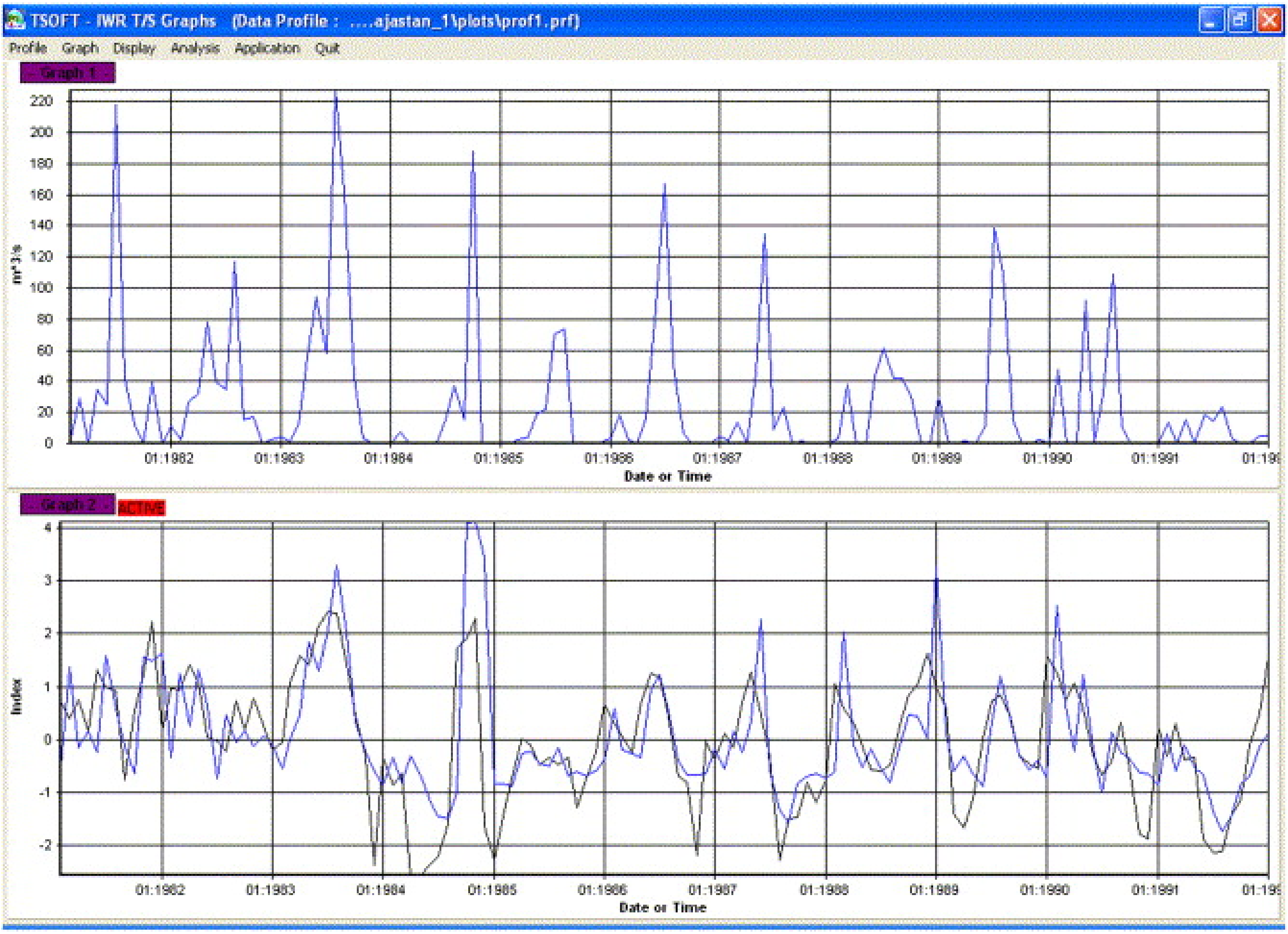

Fig. 4. Example screen showing graphs of areal monthly rainfall (top plot) and time series of 3 months' running SPI and EDI values (bottom plot). Both examples are for arbitrary selected polygon – a district in Rajasthan state of India. The legend for each plot, color schemes, scaling options and additional analysis with the displayed time series are available through various options under “Graph”, “Display” and “Analysis” menu items.

Drought summary information allows the areal extent and pattern of droughts for a specific year (or season of a year) to be examined using either actual indices extracted or *run/spell characteristics*. In both cases, it will be necessary to select the summary information required from one of the stored array attributes and to specify the ranges and colors of the drought index categories to be used for classifying the polygons. For the SPI index it has been found useful to set the minimum value to –2.5, the interval to 0.5 and the number of groups to 9. When mapping the DI (deciles) values based on the frequency data, it is suggested that five groups are used with a minimum value of 0 and an interval of 20. However, users have full flexibility in defining drought categories in any way desired.

The final result is a map of color coded index values for those polygons that have data associated with them (Fig. 5). To start another mapping with a different index, the existing one must be removed. A legend is not drawn on the Map as facilities to do this neatly are not available within the Map Objects development software. It is possible that a better way of doing this will be found in the future.

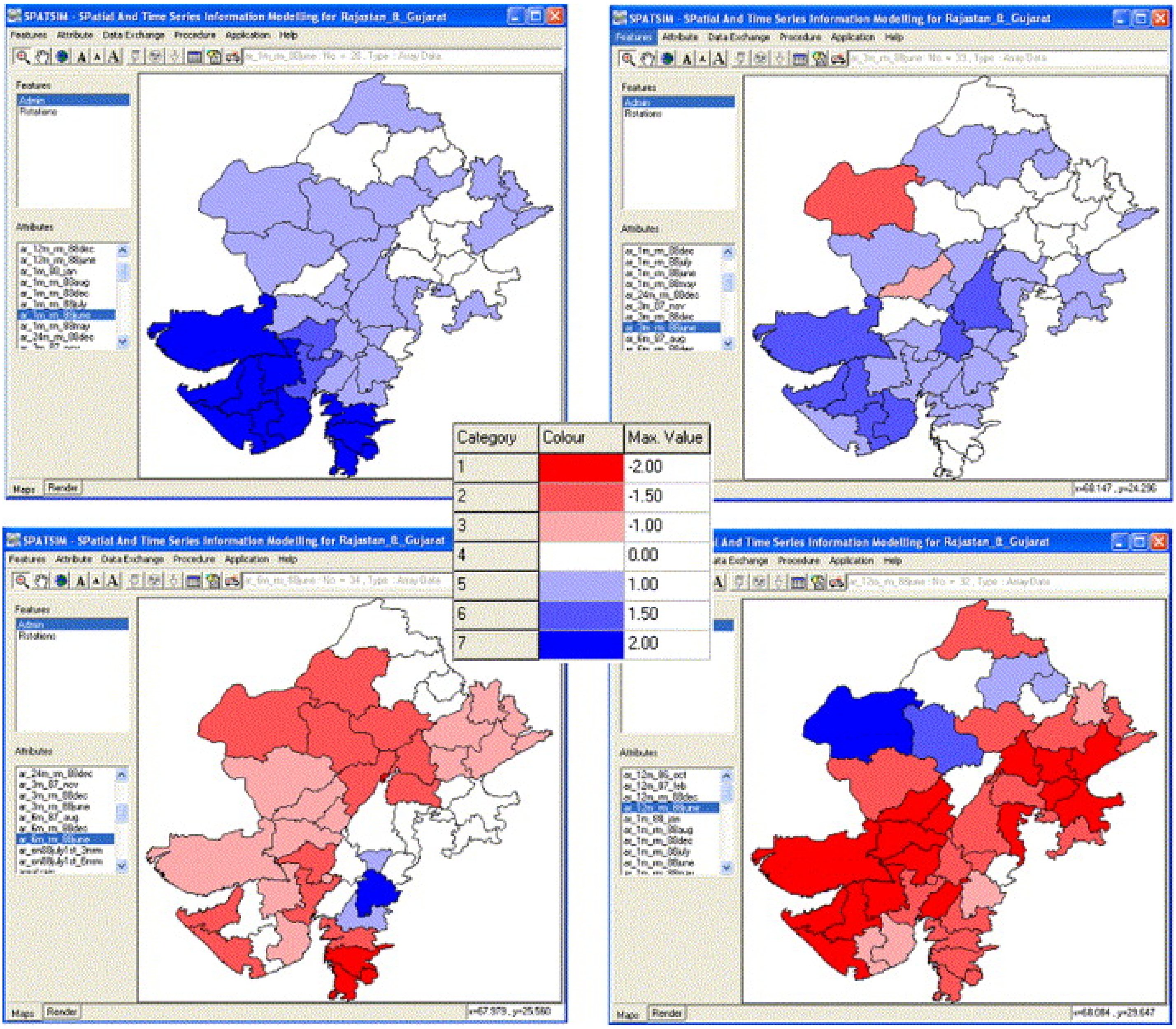

Fig. 5. Example screens with rendered maps of Rajasthan and Gujarat states in west India, showing district-wise distribution of 1 (top left), 3 (top right), 6 (bottom left) and 12 (bottom right) months' running SPI values ending June 1988. The box in the center shows the SPI ranges and corresponding color scheme used in all four cases.

Both the time series displays of TSOFT, as well as the color coded maps can be saved to graphics files for inclusion in reports or presentations. It is also possible to save the time series data from TSOFT to a text file that can be imported into a spreadsheet package or other software that have more flexible facilities for creating additional graphs and visual displays.

5. Examples of software application in drought studies

To date, the software for drought analyses has been used to quantify various aspects of droughts in the context of southwest Asia which includes west India, Pakistan and Afghanistan. The monthly precipitation data from almost 100 available meteorological stations in the region were analyzed using the SPI. The period of analysis has covered predominantly the years from 1950 to 2000, but varied between countries depending on the availability of the data. The analysis has been carried out at the scale of small administrative sub-divisions (districts or provinces) within each country. It is shown that annual meteorological droughts of different extremities (moderate, severe and extreme – as defined by the SPI thresholds) occur in the region less than once in 5 years and not every year as often is incorrectly perceived. Moderate droughts occur on average once in 7 or 8 years and more severe events are rare. The maps of drought distribution have been constructed separately for each state/country (Fig. 6) to illustrate that drought frequency can vary even within one state – between districts. That study dealt with annual droughts only, which, within the context of the software, means that single annual values of SPI were analyzed and their frequency quantified for each polygon. A more detailed analysis of drought development within each particular year is necessary and possible using the same software. It is possible to define an "early season drought", which results from the delay of monsoon rains, "mid season drought", which results from the interruptions in monsoon rains and "late season drought", due to early withdrawal of a monsoon. All these "drought types" have important implications for agricultural production, need and may be assessed separately using the presented drought software.

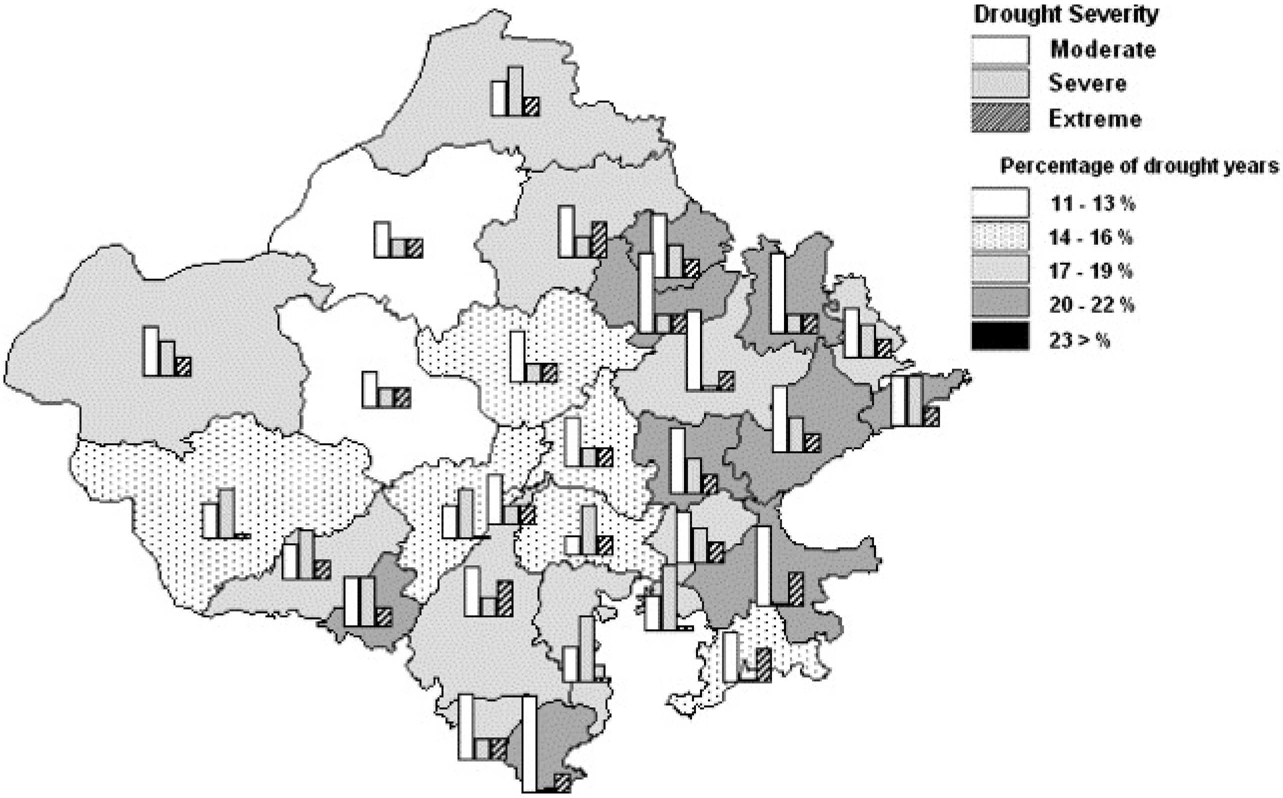

Fig. 6. District-wise distribution of moderate, severe and extreme drought years in the Indian state of Rajasthan.

Drought indices, like SPI or EDI can capture the dry and wet events similarly well, but at the same time, there may be differences in drought extremities and drought onsets, detected by different indices (e.g. Fig. 4). Analysis of various drought indices in the context of their suitability for drought monitoring is an important direction in drought research (Wilhite, 2005 and Morid et al., 2006) and tools like suggested software may facilitate this research. Drought indices like deciles, EDI or SPI can show – at different time scale – the areas which are simultaneously in drier than usual or wetter than usual conditions. While the analysis of rainfall and rainfall-related indices over short (month or season) periods may show that a drought is over, the simultaneous analysis over a longer preceding period (1–2 years or more) might indicate that a region is still in a drought spell. Fig. 5 shows several example SPATSIM screens describing the distribution of the SPI values for different durations of preceding periods (1, 3, 6 and 12 months) over the districts of the two Indian states (Rajasthan and Gujarat). It illustrates that there could have been reasonable rains in June 1988 in most of the districts (the 1 month SPI values shown on the top left picture are in a moderate to extreme wet class throughout both states). However, as the duration of the preceding period increases from 1 to 12 months, it becomes clear that both states remain in a dry condition with long-term (12 months) severe to extreme droughts dominating most of the districts (bottom right picture). Other drought indices can be used in a similar context. These types of analyses are not straightforward but could be undertaken quickly using the SPATSIM drought software and used as illustrations of developing droughts over an area for historical drought analysis and for drought monitoring in near-real-time (subject to current precipitation data being available in real-time from the responsible agencies).

6. Conclusions

A flexible package for automated estimation and analyses of meteorological drought indices has been developed and added to an existing comprehensive, water resources analysis software package (SPATSIM). All the new SPATSIM facilities have undergone preliminary testing both at IWMI and the IWR. It is recognized that further testing and user-experience is required to continuously improve the software. The IWR and IWMI are committed to continuing support of the development of the drought index components of SPATSIM and will respond to comments and suggestions from various future users. Subject to the availability of resources in the future it would be possible to add more drought indices, which are based not only on rainfall but on other hydro-meteorological data as well.

The 'Help' facilities are being added to and improved whenever problems, or better ways of explaining methods, are identified. It can be noted, however, that individual users have the ability to modify their own versions of the 'Help' files. All the help information is stored within .html files that have been created using Microsoft Word.

The addition of drought estimation routines has certainly enhanced the value of the SPATSIM software itself. It also provides the specific target groups (researchers or responsible agencies dealing with drought analyses) with a comprehensive modeling and data processing tool. This tool has already been extensively used for regional drought analyses in southwest Asia and Iran, but its geographical applicability is not limited. Besides drought analyses, the tool can also be used for a multitude of other water resources applications. It is accepted that precipitation-based indices of drought may not always provide an adequate assessment of the severity of a drought event, other meteorological factors (temperature and associated evaporation), as well as the level of storage in reservoirs, may also play a role. However, in many developing countries rainfall estimates are often the most readily available information upon which to base a regional drought analysis. The SPATSIM package already includes facilities to apply several rainfall–runoff models which incorporate reservoir water balance components (Hughes and Forsyth, in press). The package can therefore also be used to assess water supply droughts in situations where artificial storage plays a major role, as well as where water supplies are dependent upon run-of-river flows. This assumes, however, that there are sufficient resources (information and expertise) available to calibrate the models and generate reliable estimates.

Because the same package may be used by various organizations in a country or a region, it could facilitate the development of national/international communities of practice, where assessments are made using the same algorithms and software and therefore where the results can be easily exported, imported, reproduced and analyzed at different physical locations. It is anticipated that the software developed should be a useful addition to decision support tools for drought analyses and mitigation.

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References

Bruwer, 1990 J.J. Bruwer, Drought policy in the Republic of South Africa, *Proceedings of the SARCCUS Workshop on Drought, June 1989* (1990) ISBN 0 949986 24 0.

Byun and Wilhite, 1996 H.R. Byun and D.A. Wilhite, Daily quantification of drought severity and duration, *Journal of Climate* 5 (1996), pp. 1181–1201.

Frere and Popov, 1979 M. Frere and G.F. Popov, Agro meteorological crop monitoring and forecasting, *Plant Production and Protection Paper 17*, FAO, Rome (1979).

Gibbs and Maher, 1967 W.J. Gibbs and J.V. Maher, Rainfall deciles as drought indicators, *Bureau of Meteorology Bulletin No. 48*, Commonwealth of Australia, Melbourne (1967).

Guttman, 1998 N.B. Guttman, Comparing the palmer drought index and the standardized precipitation index, *Journal of American Water Resources Association* 34 (1998), pp. 113–121.

Hughes, 2004 D.A. Hughes, Incorporating ground water recharge and discharge functions into an existing monthly rainfall–runoff model, *Hydrological Sciences Journal* 49 (2004) (2), pp. 297–311.

Hughes and Forsyth, in press Hughes, D.A., Forsyth, D.A. A generic database and spatial interface for the application of hydrological and water resource models. Computers and Geosciences, in press.

Hughes and Münster, 2000 Hughes, D.A., Münster, F., 2000. Hydrological information and techniques to support the determination of the water quantity component of the ecological reserve. Water Research Commission Report TT 137/00, Pretoria, South Africa, 91 pp.

Hughes and Smakhtin, 1996 D.A. Hughes and V.U. Smakhtin, Daily flow time series patching or extension: a spatial interpolation approach based on flow duration curves, *Hydrological Sciences Journal* 41 (1996) (6), pp. 851–871.

Khan, 1998 Y. Khan, Climate and Dryland Ecology, Rawat Publications, Jaipur and New Delhi, India (1998) 188 pp..

Lloyd-Hughes and Saunders, 2002 B. Lloyd-Hughes and M.A. Saunders, A drought climatology for Europe, *International Journal of Climatology* 22 (2002), pp. 1571–1592.

McKee et al., 1993 T.B. McKee, N.J. Doesken and J. Kleist, The relationship of drought frequency and duration to time scales, *Preprints, Eighth Conference on Applied Climatology, January 17–22, Anaheim, California* (1993), pp. 179–184.

Morid et al., 2006 S. Morid, V.U. Smakhtin and M. Moghaddasi, Comparison of seven meteorological indices for drought monitoring in Iran, *International Journal of Climatology* 26 (2006), pp. 971–985.

Palmer, 1965 W.C. Palmer, Meteorological Drought Research Paper No. 45, U.S. Department of Commerce Weather Bureau, Washington, DC (1965).

Palmer, 1968 W.C. Palmer, Keeping track of crop moisture conditions, nationwide: the new crop moisture index, *Weatherwise* 21 (1968), pp. 156–161.

Petrasovits, 1990 I. Petrasovits, General review on drought strategies, *Transactions of the 14th Congress on Irrigation and Drainage, Rio de Janeiro* vol. 1-C, International Commission on Irrigation and Drainage (ICID) (1990), pp. 1–12.

Rossi and Cancelliere, 2003 G. Rossi and A. Cancelliere, At site and regional drought identification by REDIM model, *Tools for Drought Mitigation in Mediterranean Regions*, *Water Science and Technology Library* vol. 44, Kluwer Academic Publishers, Netherlands (2003), pp. 37–54.

Sastri, 1993 A.S.R.A.S. Sastri, Agricultural drought management strategies to alleviate impacts: examples from the arid and sub humid regions of the Indian Subcontinent. In: D.A. Wilhite, Editor, *Drought Assessment, Management, and Planning: Theory and Case Studies*, Kluwer Academic Publishers, Dordrecht (1993), pp. 65–86. Abstract-EconLit

Shafer and Dezman, 1982 B.A. Shafer and L.E. Dezman, Development of a surface water supply index (SWSI) to assess the severity of drought conditions in snowpack runoff areas, *Proceedings of the Western Snow Conference*, Colorado State University, Fort Collins, Colorado (1982), pp. 164–175.

Smakhtin, 2001 V.U. Smakhtin, Low-flow hydrology: a review, *Journal of Hydrology* 240 (2001), pp. 147–186.

Smakhtin and Hughes, 2004 Smakhtin, V.U., Hughes, D.A., 2004. Review, Automated Estimation and Analyses of Drought Indices in South Asia. IWMI Working Paper N 83 – Drought Series Paper No. 1. Colombo, Sri Lanka, 24 pp.

Tate et al., 2000 Tate, E.L., Meigh, J.R., Prudhomme, C., McCartney, P.M., 2000. Drought assessment in Southern Africa using river flow data. DFID report 00/4. London, UK.

Wilhite, 2005 In: D.A. Wilhite, Editor, *Drought and Water Crises: Science, Technology and Management Issues*, CRC Press and Taylor and Francis, NY (2005) 406 pp..

Wu et al., 2001 H. Wu, M.J. Hayes, A. Welss and Q. Hu, An evaluation the standardized precipitation index, the China-*z* index and the statistical *z*-score, *International Journal of Climatology* 21 (2001), pp. 745–758.

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