GIS based graphical user interface for irrigation management

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ABSTRACT

A geographic information system (GIS) based graphical user interface for irrigation management within an ArcGIS customization has been developed using Visual Basic for Applications for estimation of spatially distributed irrigation water requirements. It is capable of providing an appropriate framework for manipulating, visualizing and analyzing spatial data to support decision making in irrigation management. Its application is demonstrated through a case study for use in the field.

Key words | ArcGIS, decision making, graphical user interface, irrigation management, net irrigation requirement, reference evapotranspiration

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INTRODUCTION

Irrigation is one of the most important inputs for efficient and sustainable agricultural production (Gundogdu *et al.* 2002; Ortega *et al.* 2005). According to the Food and Agriculture Organization (FAO), one of the biggest challenges for agriculture in the coming decades will be to ensure food security for the world's steadily growing population (Bergez *et al.* 2012). Proper management of an irrigation system reduces water demand, which leads to water saving for other uses, improves agricultural productivity, and further helps in reduction of the environmental impact of irrigation (Hargreaves *et al.* 1985; Suryavanshi & Reddy 1986; Bastiaanssen *et al.* 2000). Irrigation management is therefore of paramount importance to irrigation professionals/planners/managers, for it involves multi-tasks and multi-stakeholders with varying goals. It is of common experience that spatial and temporal variabilities create problems for traditional irrigation management support systems (Lin *et al.* 2004).

Customization of geographic information systems (GIS) with Visual Basic for Applications (VBA) can be a solution for irrigation management. Most of the data related to irrigation management is complex as it is both temporally and spatially distributed in nature (Pervez & Hoque 2008; Naidu & Giridhar 2011). Its integration has led to the introduction of GIS and other technologies (Martin 1996; Bastiaanssen & Bos 1999; Bioggio & Ding 2001; Kjelds & Storm 2001; Nixon *et al.* 2001; Su & Wen 2001; Ray *et al.* 2002; Liang & Wu 2012) in irrigation management. GIS play an important role in transferring information in easily communicable form, such as maps, to farmers, planners and experts for irrigation planning and management (Maguire *et al.* 1991; Goodchild 1992; Ray *et al.* 2000; Muthanna & Amin 2003; Todorovic & Steduto 2003; Suresh Babu *et al.* 2012).

GIS have been widely applied in all scientific fields and practical activities. With environmental management, their use covers a broad spectrum, including a simple formula, and visualization of natural data as maps, visualization of pollutant concentrations in the environment and their spatial distribution (Gajos & Sierka 2012). Sheate *et al.* (2012) developed a methodology for mapping ecosystem services using GIS and readily available, existing land use/land cover datasets. Karteris *et al.* (2016) used GIS extensively to extrapolate the results from the building to the city scale and

doi: 10.2166/ws.2016.081

worked out a green sustainable strategy for the Mediterranean using environmental modelling.

ArcGIS is one of the most commonly used GIS applications in the irrigation and water resource management sectors (Tsihrintzis *et al.* 1996). It can be customized with the VBA development environment, which is fully supported by ArcGIS. This capability can be used to develop an essential tool for modeling of spatially distributed irrigation water requirements (Teixeira & Pereira 1992; Choudhury *et al.* 1994; Yamashita & Walker 1994; Hales & Burton 2000; Heinemann *et al.* 2002; Rao *et al.* 2004; Fortes *et al.* 2005; Lozano & Mateos 2008; Raut *et al.* 2008; Dhakal 2010). No such work has yet appeared in the literature in which ArcGIS customization has been developed using VBA for estimation of spatially distributed irrigation water requirements.

Thus, the present study was undertaken with the specific objective of developing a graphical user interface for irrigation management (GUIIM) within an ArcGIS customization using VBA for estimation of the spatially distributed irrigation water requirements. Its application is demonstrated through a case study area of Lakhnauta Minor of the Sidholi Distributary of the Upper Ganga Canal (UGC) system of Uttarakhand State, India through generation of thematic maps of rainfall, effective rainfall, daily reference evapotranspiration, daily crop evapotranspiration, and net irrigation requirement (NIR).

DEVELOPMENT OF INTERFACE

By customization with VBA employing Visual Basic script, an interface is developed within the framework of ArcGIS for computation of spatially distributed irrigation water requirement. Weather and crop data form the input to generate thematic raster maps for effective rainfall, reference evapotranspiration, daily crop evapotranspiration, and in turn, NIR. Standard methods recommended by the FAO (Mateos *et al.* 2002; Yoo *et al.* 2008) have been used for computation of evapotranspiration and irrigation water requirements. Temperature, solar radiation, relative humidity, precipitation, and crop data are used for computation of evapotranspiration and reference evapotranspiration. For mapping of the rainfall and effective rainfall, rainfall data are the primary inputs for computation of irrigation water requirement (Hargreaves & Samani 1985; Allen *et al.* 1998; Ray & Dadhwal 2001; Irmak *et al.* 2003; Tabari *et al.* 2013). The flowchart for development of the irrigation water requirement interface is presented in Figure 1. For ease in functioning, a new toolbar called the irrigation requirement interface tool has been developed to analyze, interpolate, and produce output maps which can be developed within ArcGIS using VBA. This tool contains buttons, input box and menus for better visual performance and easy user interaction. This tool contains three menus, i.e. Rainfall, Reference ET (ET_o) and Crop ET (ET_c), for estimation of irrigation requirement.

The point rainfall data are used as rainfall (P) for computation of effective rainfall (P_{eff}) using the following formula:

$$P_{eff} = \mathrm{P}_{coff} \times P \quad (1)$$

where P_{coff} is the rainfall coefficient. An inverse distance weighted (IDW) interpolation technique is employed for preparation of the effective rainfall thematic map. The optimal power (p) value is fixed at 2 while the search neighborhood value is fixed at 12.

The development of the interface for each component is described below.

Irrigation requirement interface tool

This interface tool is the main processing tool to analyze, interpolate, and produce output maps developed within ArcGIS using VBA, as shown in Figure 2. It contains menus/modules for Rainfall, Reference ET (ET_o), Crop ET (ET_c), and irrigation requirement.

The irrigation requirement module is used to produce a thematic raster map of the irrigation requirement for the field layer, as shown in the flowchart in Figure 3. As seen from this figure, the Rainfall menu is used to update rainfall and rainfall coefficient data and to produce an interpolated thematic raster map of rainfall and effective rainfall. Weather data required for computation of reference evapotranspiration can be updated from the Reference ET menu. The Reference ET menu allows selection from the six FAO recommended methods for computing reference evapotranspiration: FAO Penman-Monteith method, Irmak, Tabari H,

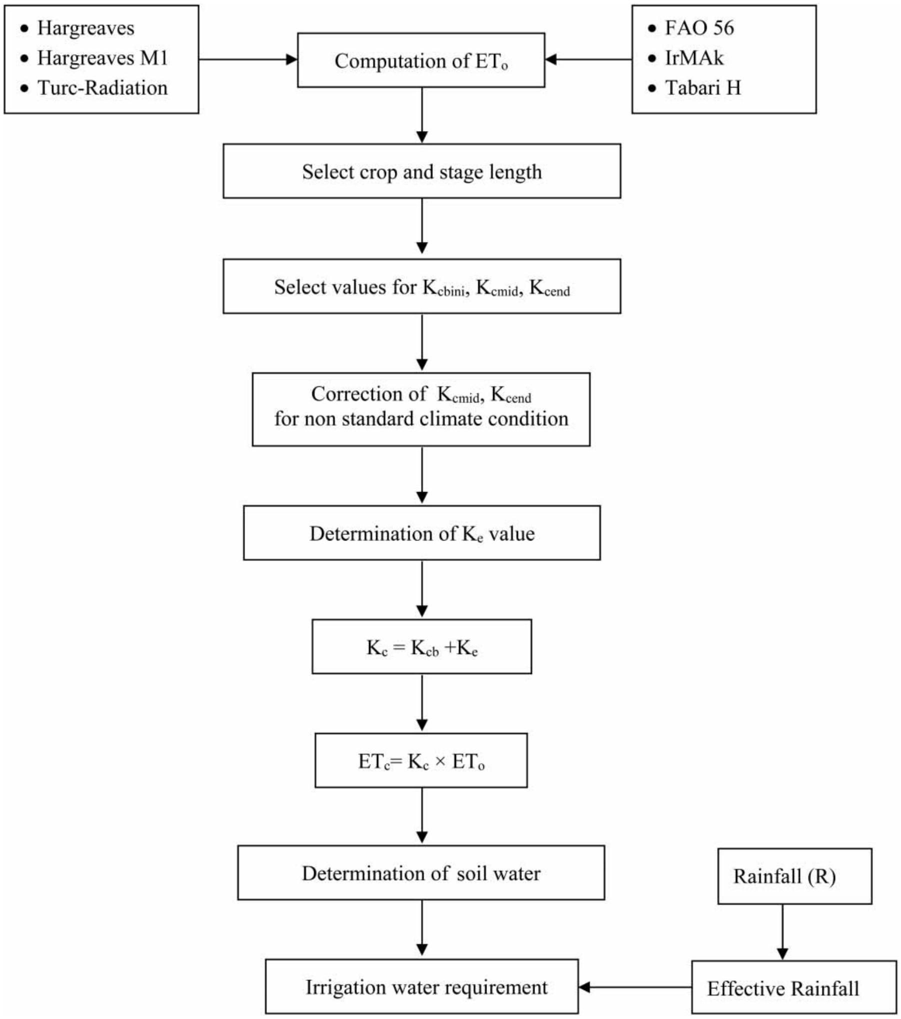

Figure 1 | Flowchart for development of irrigation water requirement interface.

Hargreaves, Hargreaves M1 and Turc-Radiation. From the same Reference ET menu, the reference evapotranspiration raster thematic map for field layer can be generated. For updating crop data and making the crop evapotranspiration raster map, the Crop ET menu is to be used.

Rainfall menu and its module

The Rainfall menu and its modules are presented in Figure 4(a). As also described above, it allows updating of rainfall data and creation of an interpolated raster map for rainfall and effective rainfall in the area of interest. This module first allows selection of rainfall layer and updating of rainfall and rainfall coefficient data through a rainfall graphical window. Further, it helps in the creation of the raster map of rainfall and effective rainfall. The Rainfall menu contains five attached modules, namely Updated Rainfall, Rainfall Raster, Effective Rainfall Raster, Rainfall Raster Fields, and P_{eff} Raster Fields (Figure 4(b)).

The Updated Rainfall module allows first the selection of the layer for rainfall (Figure 5). After selecting the rainfall layer it allows links to the rainfall graphical window. The graphical window of rainfall allows the changing and editing of the rainfall and rainfall coefficient values. After editing the values, the update button allows the updating and storing of the new values with the help of the command button. The update command also computes the effective rainfall for each station and updates its value in the respective cells.

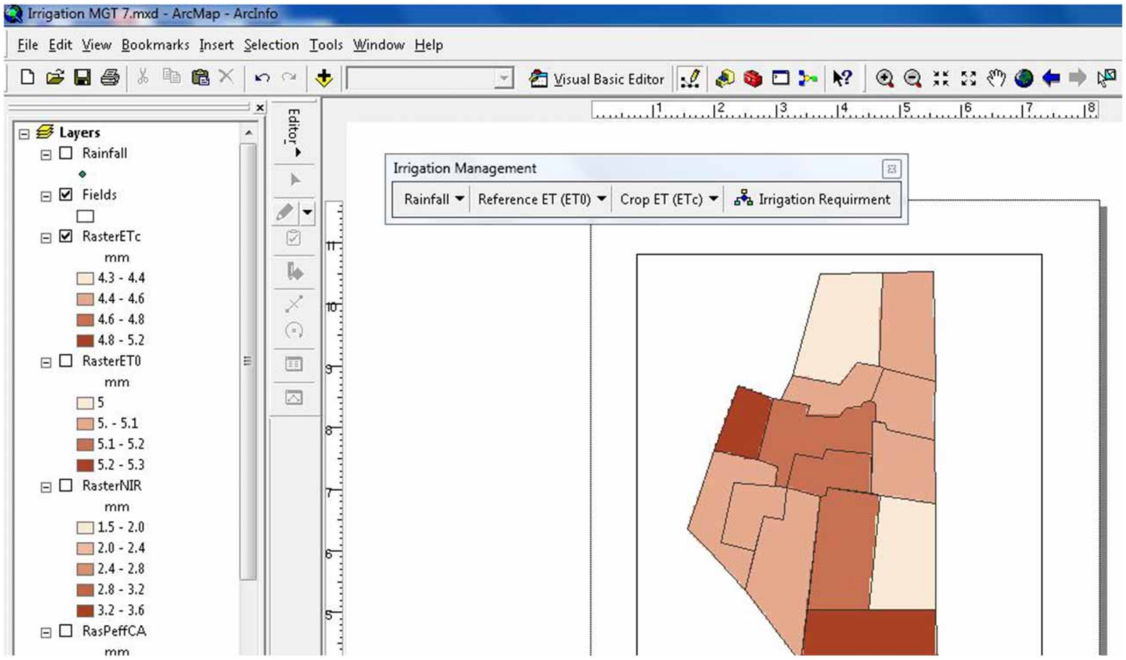

Figure 2 | Irrigation requirement interface tool.

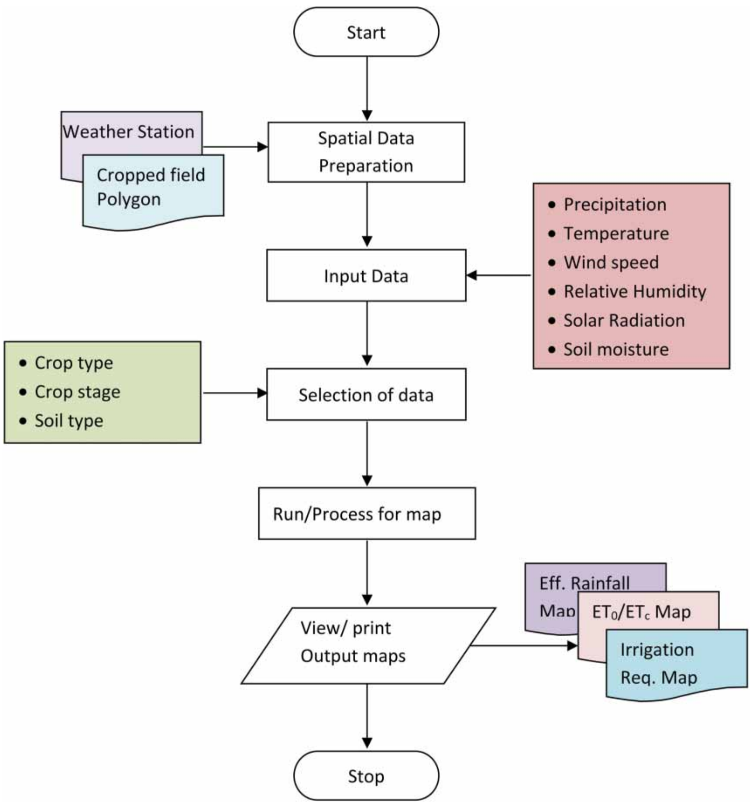

Figure 3 | Flowchart of irrigation management interface tool.

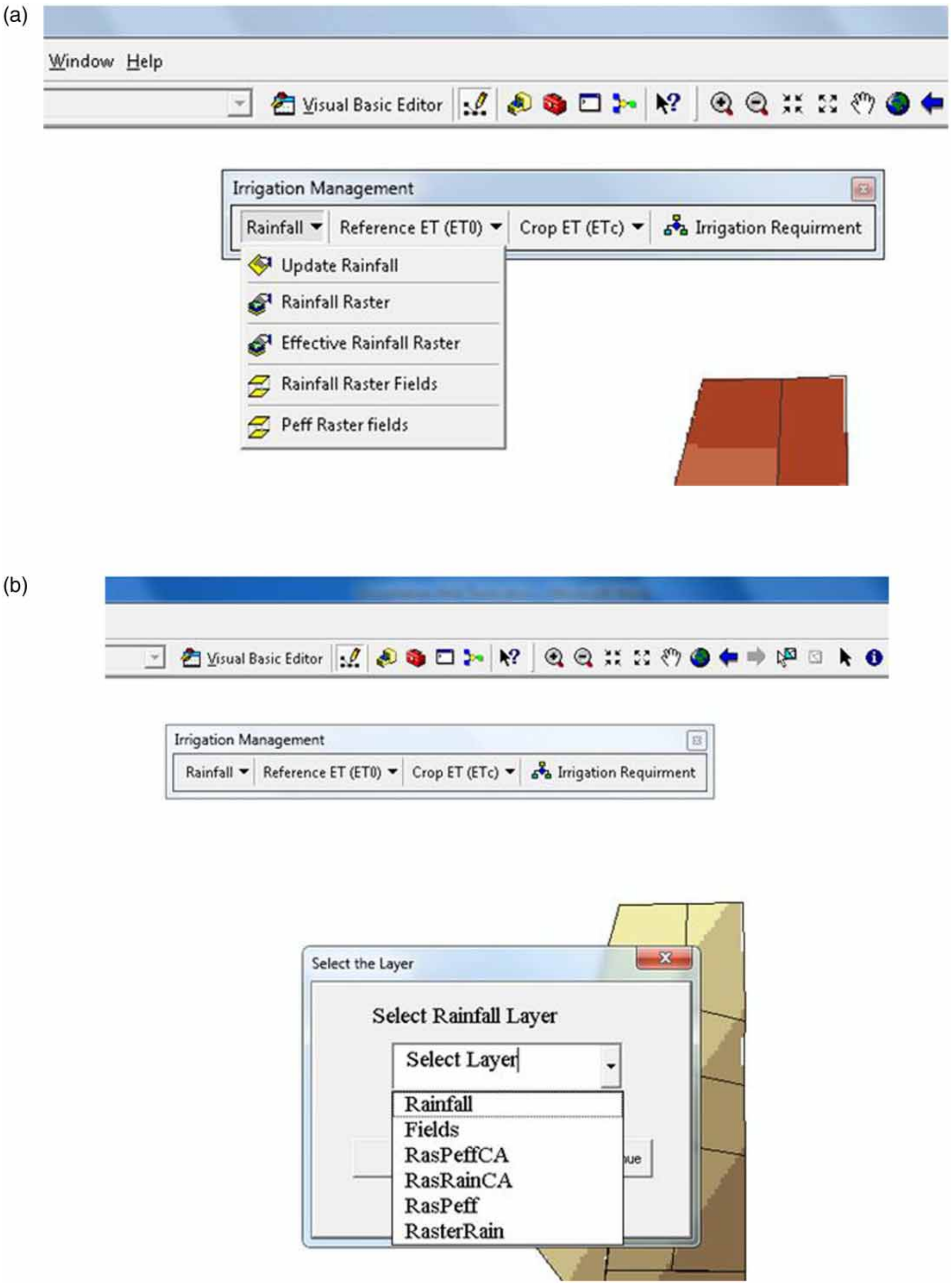

Figure 4 | (a) The Rainfall menu and its modules; (b) graphical window to select layer for rainfall.

The Rainfall Raster module allows access to the rainfall layer and its rainfall field data. This module uses the rainfall layer and its rainfall field data as input and interpolates rainfall data using inverse weight techniques to produce a rainfall raster map of the area included by the points. The Effective Rainfall Raster module allows access to the rainfall layer and its effective rainfall field data. This module uses the rainfall layer and its effective rainfall field data as input and for interpolating rainfall data using the same technique to produce an effective rainfall raster map of the area included by the points.

The Rainfall Raster Fields module uses the rainfall raster map and fields polygon as a mask and extracts the rainfall raster map to produce a rainfall raster map of the study

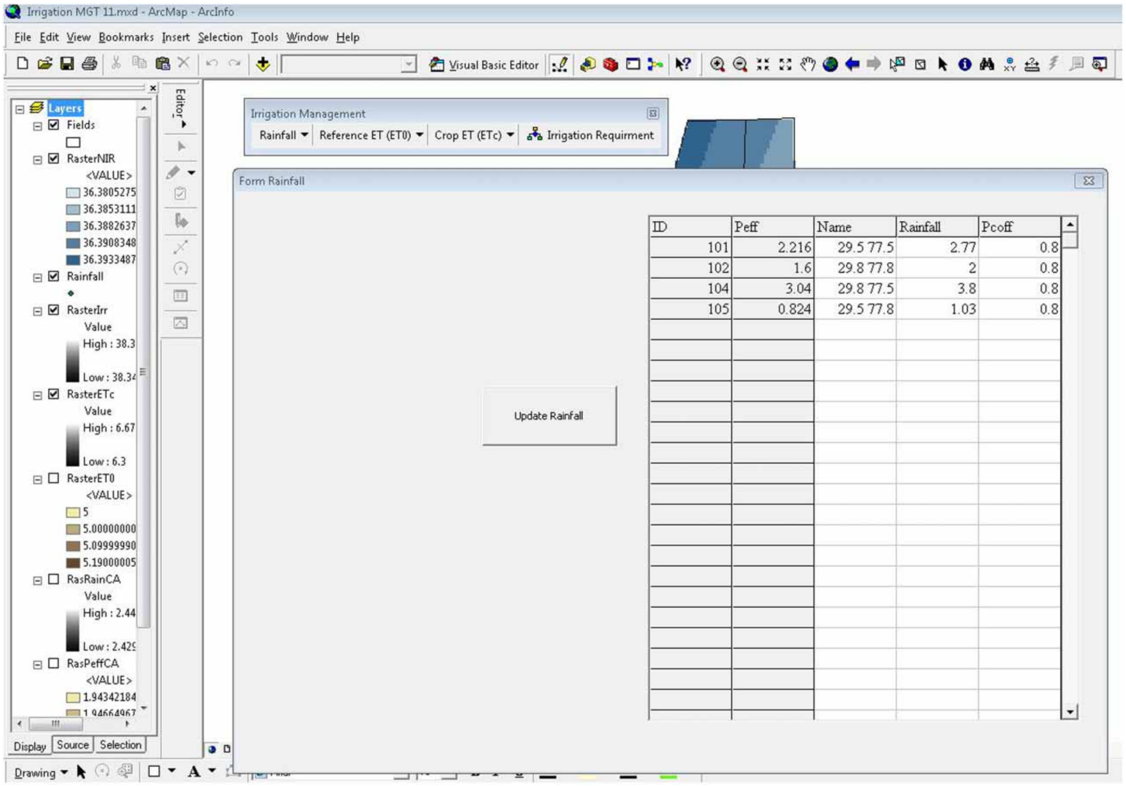

Figure 5 | Rainfall graphical window to allow updating of the rainfall parameter.

area only included by the field layer. The P_{eff} Rainfall Raster Fields module uses the effective rainfall raster map and fields polygon as a mask and extracts the rainfall raster map to produce the rainfall raster map of the area of interest.

Reference ET (ET_o) menu and its module

The Reference ET (ET_o) menu and its attached modules allow updating of the weather data required for its computation and allow the creation of an ET_o raster map for the field layer (Figure 6(a)). This module allows selection of the field layer and the calculation needed, and further updating of the weather and computed data. Further, it allows development of a raster map of ET_o. Its menu contains two modules, namely Update Weather and Raster ET_0.

The Update Weather module allows the selection of a polygon layer of the cropped field and allows linking of the ET_o graphical window. The ET_o graphical window allows selection of the weather data from the existing station available in the database. The weather data listed in the ET_o graphical window are loaded from the prepared database inside the interface and can be edited and saved for further uses. The weather data can be used for each field or can be used for all fields at once. After editing, the weather data update button allows updating and the storing of the new values.

ET_0 is computed inside its graphical window through respective command buttons. Different methods of ET_0 computation can be triggered by respective command buttons, as for example, the FAO Penman-Monteith equation, Irmak and Hargreaves methods. The computed ET_o values appear in its fields in every row of the grid. The update command updates all the weather data and computes the ET_o value in respective cells and in its database for further use. The graphical window for ET_o allows updating of the weather parameter and computation of ET_o (Figure 6(b)).

The Raster ET_o module allow access to the field layer and its ET_o field data. This module uses the rainfall layer

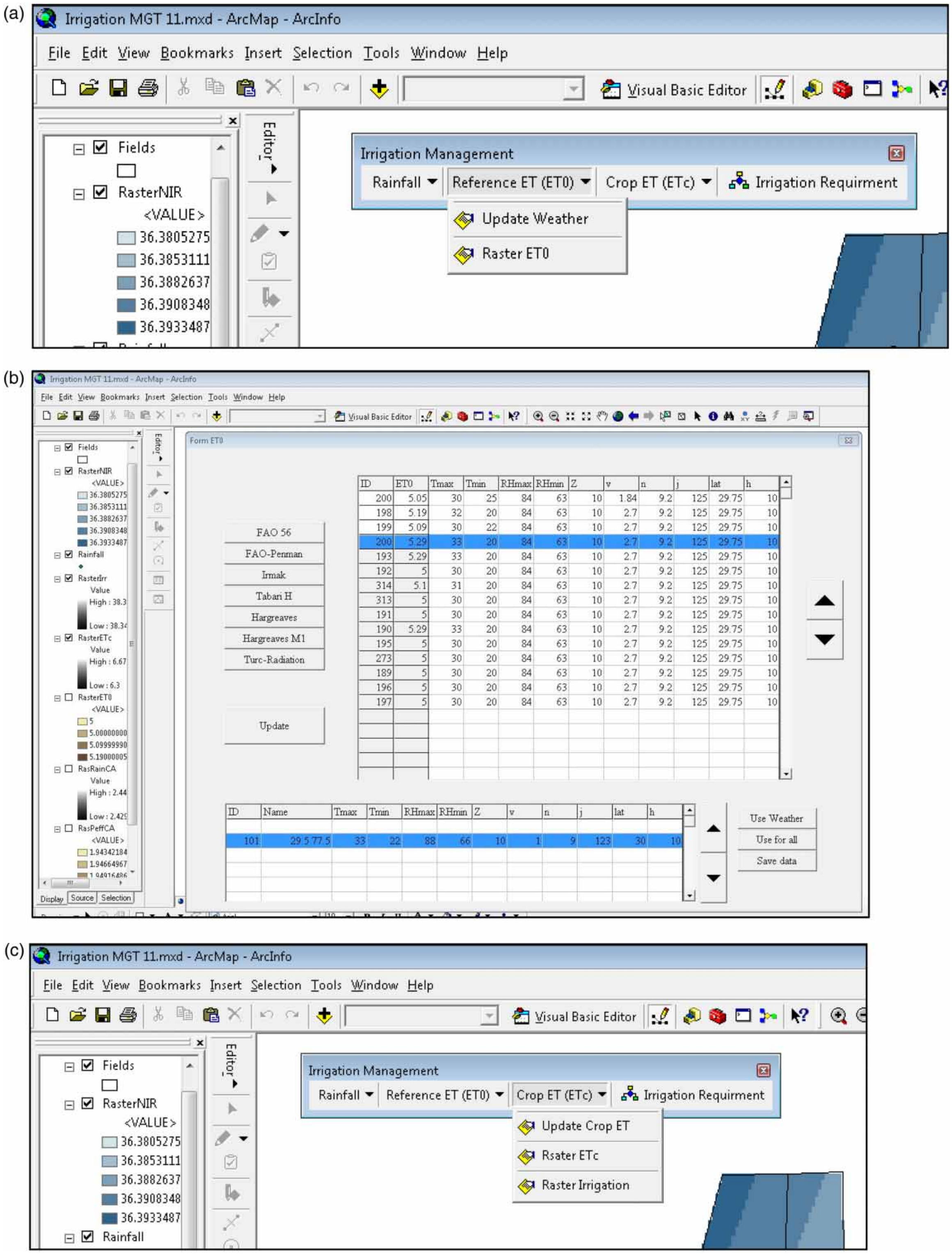

Figure 6 | (a) Reference ET (ET_o) menu and its modules; (b) graphical window for ET_o to allow updating of weather parameter and computation of ET_o; (c) menu for Crop ET (ET_c) along with its modules.

and its ET_o field data as input and produces the ET_o raster map.

Crop ET (ET_c) menu

The Crop ET (ET_c) menu and its attached modules allow the updating and selection of the crop data, soil data and soil moisture data required for computation of the crop evapotranspiration and irrigation requirement. This menu allows generation of the thematic raster map of the crop evapotranspiration and water requirement for the selected field layer. This module allows selection of the field layer and required calculations and updating of the crop data, soil data and soil moisture data. Further, it allows development of thematic raster maps of crop evapotranspiration and water requirement for the area of interest.

The Crop ET (ET_c) menu comprises two modules, namely Update Crop ET and Raster ET_c (Figure 6(c)). The Update Crop ET module allows first the selection of a layer for the field. After layer selection it allows links to the ET_c graphical window.

The ET_c graphical window allows selection of crop, correction of crop coefficient for local climatic conditions and performs soil water balance on the crop root zone to compute the crop water requirement (Figure 7). After editing the input, and selection and processing of data, the update button allows updating and storage of the new computed crop evapotranspiration and irrigation requirement values for each field.

The crop data listed in the graphical window of ET_c are imported from the prepared database inside the interface and can be selected for use in the soil water balance process. The computed data for crop evapotranspiration and irrigation requirement values can be used for either each field or for all fields at once and data can be updated and stored in the database using the update button. The Raster ET_c module allows access to the field layer and its ET_c field data in the field's layer attribute table. This module uses the field layer and its ET_c field data as input and process to produce a crop evapotranspiration (ET_c) raster map of the area of interest. The ET_c graphical window can perform the following task regarding

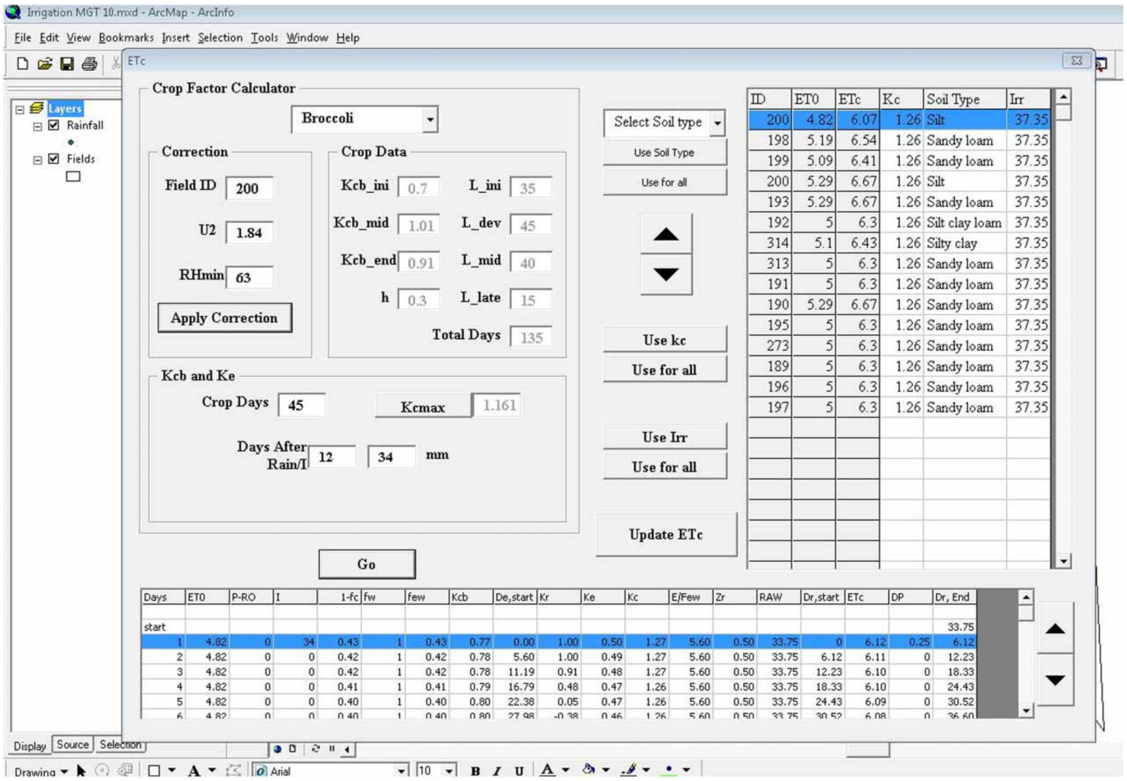

Figure 7 | ET_c graphical window for crop factor and water requirement.

computation of crop evapotranspiration and irrigation requirement.

Selection and update soil type

The soil type for each field can be selected from the drop-down combo box and can be stored by the command button. The soil type can be used for each field or used for all at once through the respective command buttons. The type of soil in each field is used for computation of crop coefficient and water requirements in cropped fields.

Crop coefficient

The dual crop coefficient facility is also added for predicting the effects of specific wetting events on the value of crop coefficient K_c by splitting K_c into two separate coefficients, one for crop transpiration, i.e., the basal crop coefficient (K_{cb}), and one for soil evaporation (K_e).

$$ET_c = (K_{cb} + K_e)ET_o \quad (2)$$

The user is allowed to select commonly used crops through the combo box. Crop data which are not available in the combo box can also be placed by the user with values defined by the user.

Correction of K_c mid and K_c end for local climate

The K_c values (FAO paper-56, table 12) used in the interface are the typical expected values of average K_c under standard climatic conditions. For local climatic conditions the K_c value needs to be corrected. The user is allowed to make adjustments for the local or specified climate. The correction of the crop coefficient for local climate conditions is possible through the command button.

Soil water balance and allocating irrigation

By calculating the soil water balance of the root zone on a daily basis, the timing and depth of future irrigations can be estimated. The module allows users to model soil water balance in the root zone and forecasting of irrigation requirement.

Irrigation management module

The irrigation management module generates the raster map of NIR. It uses the raster map of water requirement and effective rainfall, generated by the interface, to produce a thematic raster map of net irrigation.

After development of the irrigation water requirement interface it was applied in the Lakhnauta Minor of the Sidholi Distributary of UGC of Uttarakhand State, India.

Application of the interface in UGC

Study area

The UGC system is one of the largest and oldest canal systems in India. The UGC takes off from Bhimgowda Barrage at Haridwar. The discharge of UGC is around 295 cumec which runs through 272 miles of main canal and about 4,000 miles of distribution canal. The UGC system irrigates 9 lakh-ha of agricultural land of Uttarakhand and Uttar Pradesh. The Lakhnauta Minor, which takes off from the Sidholi Distributary of the UGC system, is selected as case study. The Culturable Command Area (CCA) area under study of outlet number 33 of Lakhnauta Minor is 31.16 ha. The CCA under the Sidholi Distributary is 5,916 ha. The location map of the study area is shown in Figure 8.

Spatial database preparation

Spatially distributed data for the cropped field as a polygon is required as input for the developed interface. The spatial data for the cropped field requires weather, soil and crop information. Weather data comprises maximum and minimum temperature, relative humidity, solar radiation and wind speed. Similarly crop data comprises crop type and its development stages. Rainfall data of the nearby weather stations is also required. Daily weather data from the Global Weather Data of SWAT (http://globalweather.tamu.edu/) were selected for the rainfall and weather data as input to execute the interface and simulation of irrigation

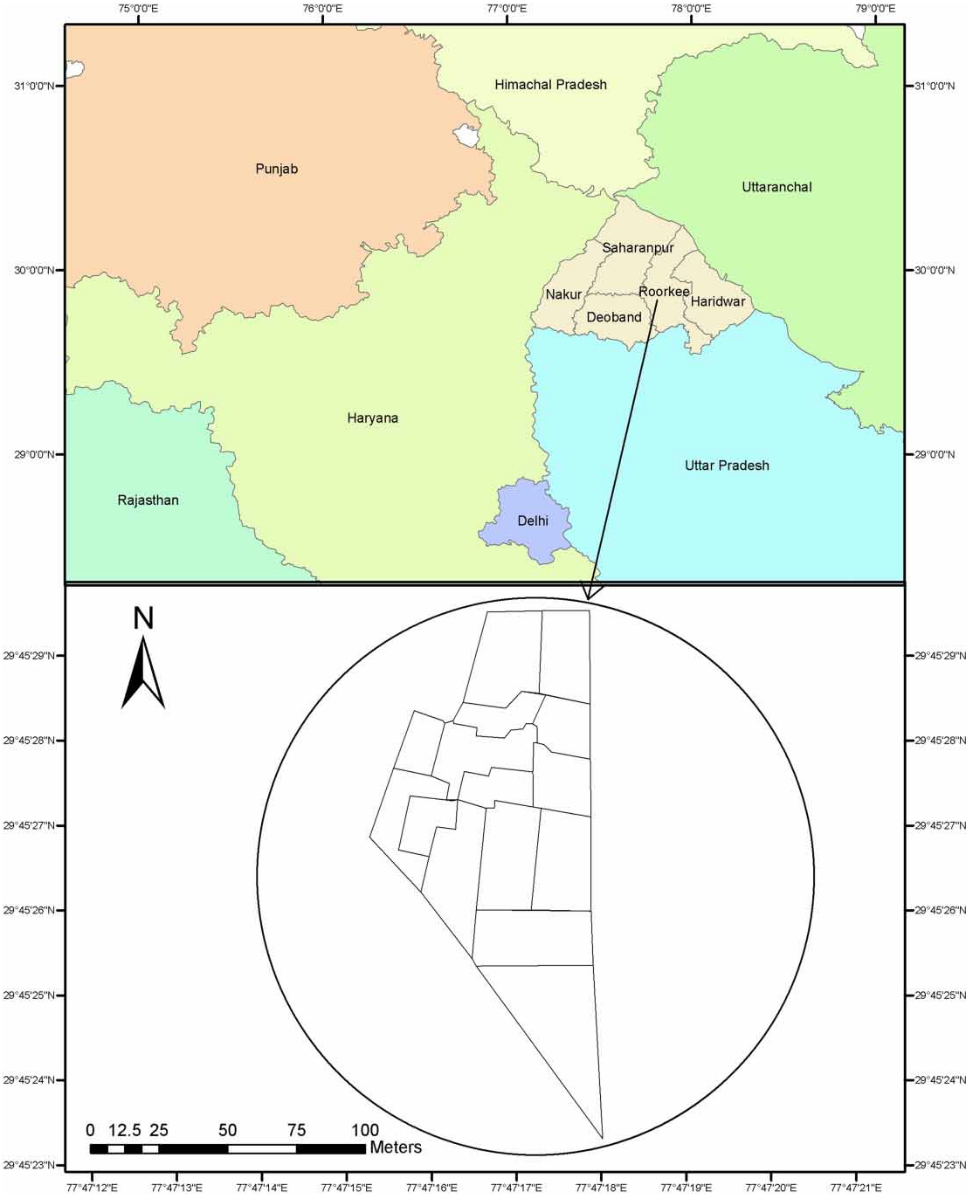

Figure 8 | Location map of the study area.

water requirement. The field's spatial distributed data for the study area are presented in Figure 9.

In this study, standard rice crop data were included in the interface and crop duration was inserted manually. Other crop information such as root zone depth and crop coefficient for respective development stage are stored inside the interface database and selected during execution of the interface. The selected soil type is sandy loam. It is assumed that soil is homogeneous and paddy crop is planted all over the study area.

Data preparation consists of preparation of the spatially distributed GIS data of the selected area with the polygon of the cropped field's boundary and the spatial points of the weather stations near the study area. Separate layers for each rainfall point data covering the field's layer and field's polygon layers are prepared using ArcGIS 9.3.

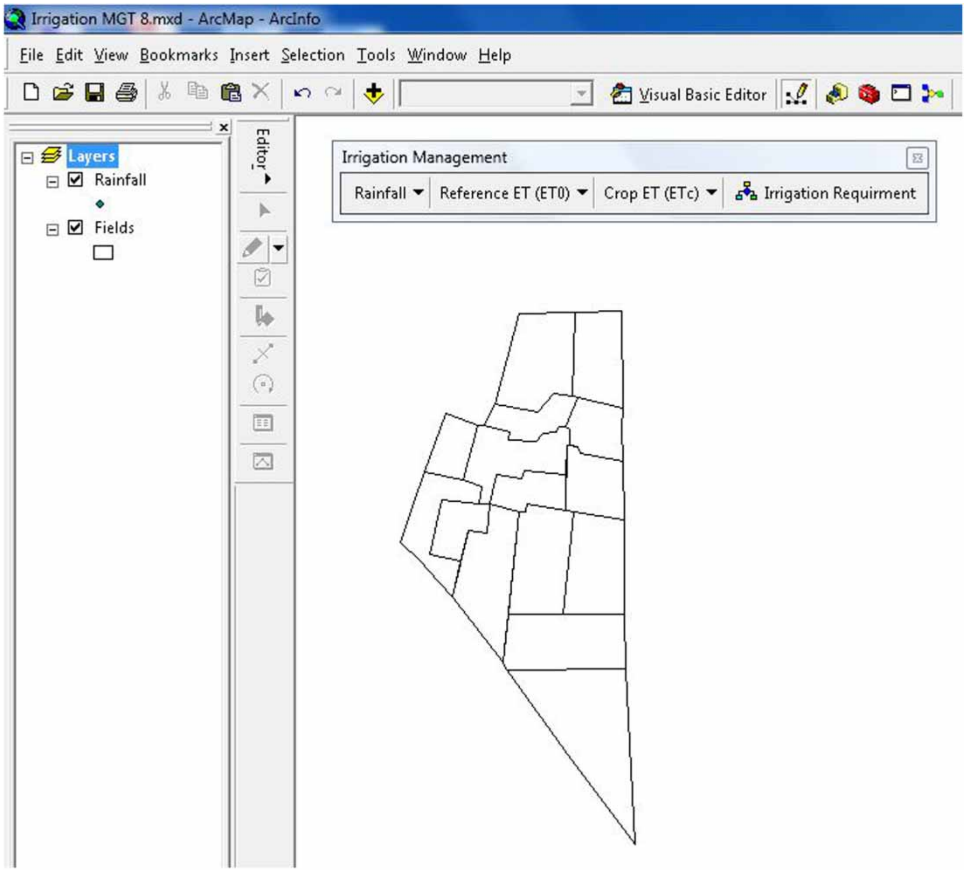

Figure 9 | The field's spatial distributed data for the study area.

The Rainfall layer contains data of rainfall (mm), runoff coefficient (P_{coff}) and effective rainfall (P_{eff}) for each distributed point, hence the field of the column for each category was prepared and linked with the attribute table of the rainfall layer. The Rainfall layer contains the rainfall field where rainfall data are stored, the P_{coff} field to store the rainfall coefficient to be used for that station and the P_{eff} field to store effective rainfall data. Similarly the field layer contains data of fields T_{max}, T_{min}, RH_{max}, RH_{min}, z, v, n, Lat, h, j, ET_o, ET_c for weather parameter input for computation of the reference evapotranspiration. Fields named K_c and ET_c are also added to store crop factor data and crop evapotranspiration data.

Processing and interface setup

The interactive tool developed within ArcGIS is used for the data input, processing of the data and developing the output thematic maps. Computations required in determining evapotranspiration and irrigation parameters are integrated within the interactive tool triggered by command buttons supported by respective codes. Setup of the interface primarily consists of input of the required data, selection of the relevant data from the list and process for the thematic map. The process also requires selection of the appropriate method of computation for reference evapotranspiration from the list provided in the interface, selection of crop data, soil data from list and processing. A flowchart of the interface setup and data processing is presented in Figure 3.

Climatic data, soil data and crop data are used as input for the model. The spatial databases of the irrigation system are always needed as an input and are modified by the model according to its need (Hashmi *et al.* 1994; Liu *et al.* 1998). The thematic maps of irrigation requirements, irrigation requirement parameters and effective rainfall maps

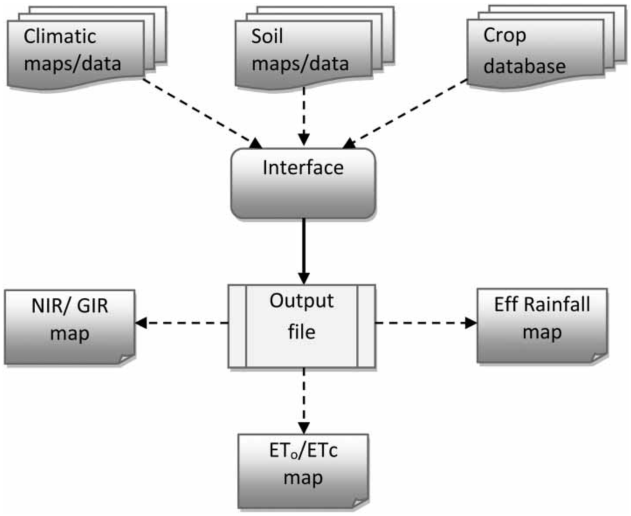

Figure 10 | Flowchart of data exchange between input/output and mechanistic model.

are visualized and stored as an output file for the model. An overview of the input/output system for the model is depicted in the flowchart presented in Figure 10.

Generation of thematic map

Spatial information is crucial for efficient irrigation management. In this study, daily weather data for December 2013 were selected to animate maps containing basic control functions to display the maps in an interactive manner. To fulfill the requirement of animated maps pertaining to weather parameters, evapotranspiration and irrigation requirements were created. The user can store and access the created maps as and when needed.

The computed values of ET_c and ET_o data for each polygon field are used to generate a thematic raster map of reference evapotranspiration and crop evapotranspiration. For interpolation, the raster IDW interpolation technique was employed. The VBA code attached to the raster map of the Reference ET and Crop ET module of the interface tool helps in generating thematic maps of the effective rainfall.

The irrigation requirement thematic raster map is generated using the irrigation requirement module in the interface tool. The module uses thematic raster maps of effective rainfall and crop evapotranspiration. A subtraction cell-by-cell technique is used to generate the irrigation requirement map. The VBA code attached to the irrigation management module of the interface tool allows the generation of a thematic map of irrigation requirement.

Generation of thematic maps using interface

The interface was used for generation of thematic maps for the selected study area with the selected weather, soil and crop data. Daily weather data from Global Weather Data for SWAT (http://globalweather.tamu.edu/) was used for the rainfall and weather data to be processed by the interface and simulate the irrigation requirement. The interface processed these data for simulation of irrigation requirement with the study area.

Generation of rainfall map and effective rainfall map

The rainfall layer was selected with four weather stations. The rainfall data for October 2013 was used as input and updated in the Rainfall graphical window and was processed by the interface to produce thematic rainfall and effective rainfall output maps. The runoff coefficient of 0.8 is employed in this study. The resultant map is presented in Figure 11.

Generation of reference evapotranspiration map (ET_o)

The weather data for October 20, 2013, was used as input in the interface and the layer of cropped field was used for processing. FAO 56 method was selected from the interface for the creation of the daily reference evapotranspiration map of the study area (Figure 12).

Generation of crop evapotranspiration map (ET_c)

The crop ET module in the interface was given as input with a spring wheat crop. The crop coefficient and crop stage data for standard climate conditions were automatically loaded from the interface data. Local climate correction was applied with the weather data automatically loaded from the interface for the field layer. The layer of cropped field was used for processing to generate the daily crop evapotranspiration map (Figure 12).

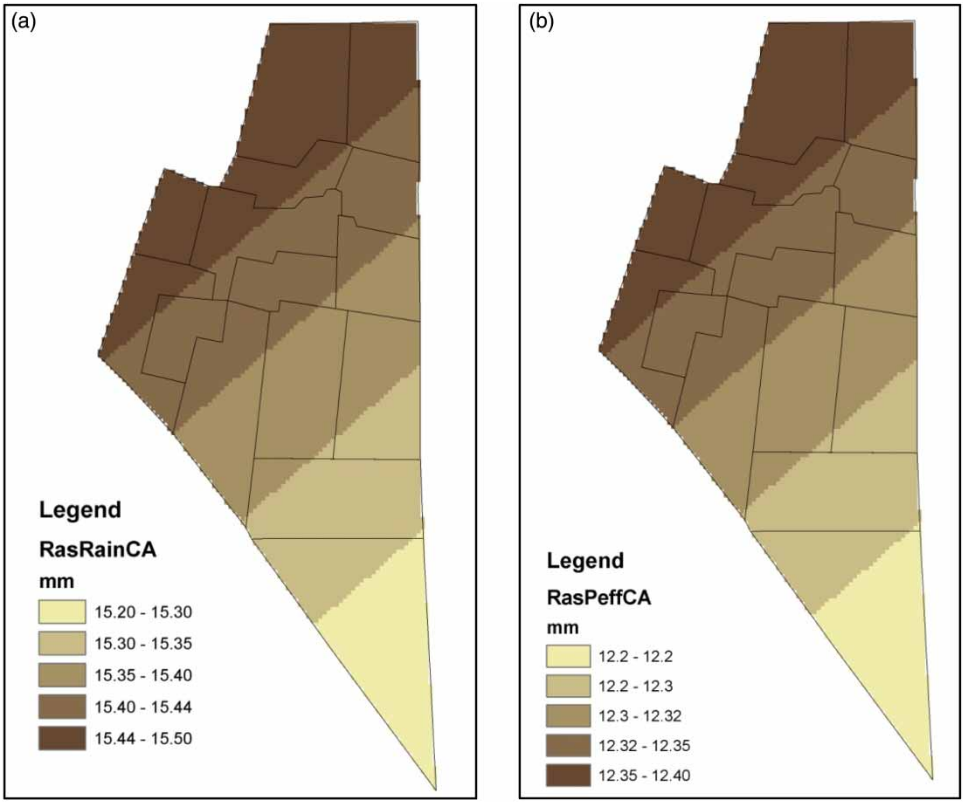

Figure 11 | (a) Rainfall raster map; (b) effective rainfall raster map of the selected area.

Generation of net irrigation requirement map

The crop data were selected and correction in the local climate was applied in the graphical window of ET_c. Initial irrigation depth of 35 mm was used as input and the interface processed the soil water balance for 15 subsequent days. Finally, the water requirement raster map was generated for the study area. The irrigation requirement module was used to generate the NIR map, which uses raster maps of effective rainfall and irrigation water requirement (Figure 13).

Thus, this tool can be used to generate raster maps of irrigation requirement parameters and is intended for use by irrigation authorities and irrigation management consortia to analyze water requirements and to make easy and quick decisions. The interface tool consists of a graphical user interface, capable of real-time simulation, and is user friendly. The developed interface is prompt in decision-making and capable of spatial irrigation management. Spatial maps can provide information more effectively. The developed spatial maps can be easily interpreted by farmers, planners and specialists for spatial irrigation management.

SUMMARY AND CONCLUSION

The study demonstrated the development and application of a GIS based graphical user interface for irrigation management (GUIIM) within an ArcGIS customization using VBA for simulation of spatial irrigation water requirements. The developed interface tool was successfully employed for Lakhnauta Minor of the Sidholi Distributary of the UGC system of Uttarakhand State, India, to generate spatial thematic maps pertaining to irrigation water requirements including reference evapotranspiration, crop evapotranspiration, rainfall and effective rainfall maps with weather,

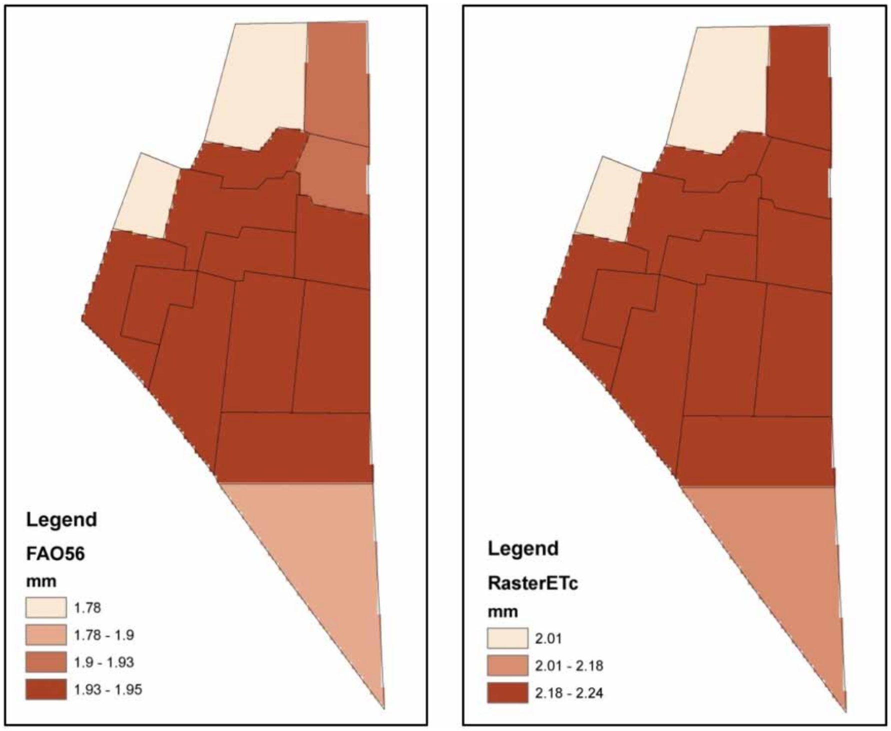

Figure 12 | Daily Reference ET (ET_O) and Crop ET (ET_C) raster maps of the selected area.

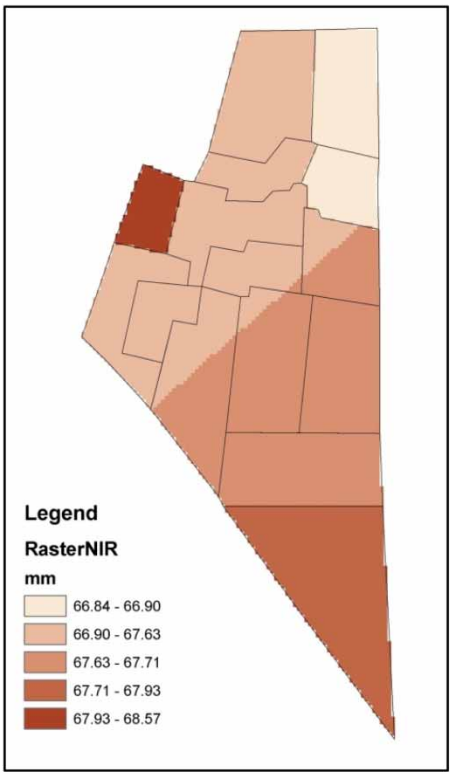

Figure 13 | NIR raster map of the study area.

crop and soil data as input. The GUIIM and generated maps can be helpful in information sharing and visualization for irrigation experts and farmers in irrigation management. The developed interface can be used by irrigation experts for generating thematic maps and further effective irrigation management regarding irrigation allocation and scheduling. Thus, ArcGIS can be customized effectively using VBA to develop a tool capable of simulating spatial irrigation water requirements, which is useful in the decision-making process in irrigation management. This interface tool can be effectively used for any command area to generate thematic maps pertaining to irrigation water requirements.

REFERENCES

Allen, R. G., Pereira, L. S., Raes, D. & Smith, M. 1998 *Crop Evapotranspiration – Guidelines for Computing Crop Water Requirements.* FAO Irrigation and Drainage Paper 56, FAO, Rome, D05109.

Bastiaanssen, W. G. M. & Bos, M. G. 1999 Irrigation performance indicators based on remotely sensed data: a review of literature. *Irrigation and Drainage System* **13** (4), 291–311.

Bastiaanssen, W. G., Molden, D. J. & Makin, I. W. 2000 Remote sensing for irrigated agriculture: examples from research and possible applications. *Agricultural Water Management* **46** (2), 137–155.
Bergez, J. E., Leenhardt, D., Colomb, B., Dury, J., Carpani, M., Casagrande, M., Charron, M. H., Guillaume, S., Therond, O. & Willaume, M. 2012 Computer-model tools for a better agricultural water management: tackling managers' issues at different scales – a contribution from systemic agronomists. *Computers and Electronics in Agriculture* **86**, 89–99.
Bioggio, M. R. & Ding, Y. 2001 An integrated regional watershed model. In: *Bridging the Gap: Meeting the World's Water and Environmental Resources Challenges, Proceedings of the World Water and Environmental Resources Congress, 20–24 May 2001, Orlando, FL*, D. Phelps & G. Sehlke, (eds), American Society of Civil Engineers, ASCE, EWRI. CD-ROM publication.
Choudhury, J., Ahmed, N. U., Idso, S. B., Reginato, R. J. & Daughtry, C. S. 1994 Relations between evaporation coefficients and vegetation indices studied by model simulations. *Remote Sensing of Environment* **50** (1), 1–17.
Dhakal, A. 2010 *Web GIS to Support Irrigation Management: A Prototype for Sagra Network, Alentejo Portugal*. Master's thesis, Universidade Nova de Lisboa, Portugal.
Fortes, P. S., Platonov, A. E. & Pereira, L. S. 2005 GISAREG – a GIS based irrigation scheduling simulation model to support improved water use. *Agricultural Water Management* **77** (1), 159–179.
Gajos, M. & Sierka, E. 2012 GIS technology in environmental protection: research directions based on literature review. *Polish Journal of Environmental Studies* **21** (2), 241–248.
Goodchild, M. F. 1992 Geographical information science. *International Journal of Geographical Information Systems* **6** (1), 31–45.
Gundogdu, K. S., Degirmenci, H. & Demirtas, C. 2002 Creation of GIS supported database in irrigation project management. In: *Sustainable Agro-Environmental Systems – New Technologies and Applications. Proceedings of Third International Symposium AGROENVIRON, 26–29 October 2002*.
Hales, A. L. & Burton, M. A. 2000 Using the IRMOS model for diagnostic analysis and performance enhancement of the Rio Cobre Irrigation Scheme, Jamaica. *Agricultural Water Management* **45** (2), 185–202.
Hargreaves, G. H. & Samani, Z. A. 1985 Reference crop evapotranspiration from temperature. *Applied Engineering in Agriculture* **1** (2), 96–99.
Hargreaves, G. H., Hargreaves, L. A. & Riley, J. P. 1985 Agricultural benefits for Senegal river basin. *Journal of Irrigation and Drainage Engineering* **111** (2), 113–124.
Hashmi, M. A., Garcia, L. A. & Fontane, D. G. 1994 Spatial estimation of regional crop evapotranspiration. *Transactions of the ASCE* **38** (5), 1345–1351.
Heinemann, A. B., Hoogenboom, G. & Faria, R. T. 2002 Determination of spatial water requirements at county and regional levels using crop models and GIS: an example for the State of Parana, Brazil. *Agricultural Water Management* **52** (3), 177–196.
Irmak, S., Irmak, A., Allen, R. & Jones, J. 2003 Solar and net radiation-based equations to estimate reference evapotranspiration in humid climates. *Journal of Irrigation and Drainage Engineering* **129** (5), 336–347.
Karteris, M., Theodoridou, I., Mallinis, G., Tsiros, E. & Karteris, A. 2016 Towards a green sustainable strategy for Mediterranean cities: assessing the benefits of large-scale green roofs implementation in Thessaloniki, Northern Greece, using environmental modelling, GIS and very high spatial resolution remote sensing data. *Renewable and Sustainable Energy Reviews* **58**, 510–525.
Kjelds, J. & Storm, B. 2001 Integrated water resources modeling water use and water quality simulation. In: *Bridging the Gap: Meeting the World's Water and Environmental Resources Challenges, Proceedings of the World Water and Environmental Resources Congress, 20–24 May 2001, Orlando, FL*, D. Phelps & G. Sehlke, (eds), American Society of Civil Engineers, ASCE, EWRI. CD-ROM publication.
Liang, X. & Wu, J. 2012 The application of GIS in the field of irrigation water management. In: *Computer Science and Network Technology, 2nd International Conference*, IEEE, Changchun, December 2012, pp. 1497–1500.
Lin, W. T., Ho, Y. F. & Su, M. D. 2004 *GIS for Irrigation Management in Irrigation Associations*. FAO Irrigation and Drainage Papers, FAO, Rome.
Liu, Y., Teixeira, J. L., Zhang, H. J. & Pereira, L. S. 1998 Model validation and crop coefficients for irrigation scheduling in the North China Plain. *Agricultural Water Management* **36** (3), 233–246.
Lozano, D. & Mateos, L. 2008 Usefulness and limitations of decision support systems for improving irrigation scheme management. *Agricultural Water Management* **95** (4), 409–418.
Maguire, D. J., Goodchild, M. F. & Rhind, D. W. 1991 *Geographical Information Systems: Principles and Applications, Vol. II*. John Wiley & Sons, New York.
Martin, M. 1996 Application of GIS in irrigation districts: how much and when to irrigate. *Sixth International Conference on Computers in Agriculture*, Mexico, June 1996, pp. 645–649.
Mateos, L., Lopez, I. & Sagardoy, J. A. 2002 SIMIS: the FAO decision support system for irrigation scheme management. *Agricultural Water Management* **56** (3), 193–206.
Muthanna, G. & Amin, M. S. M. 2003 Irrigation planning using geographic information system: a case study of Sana'a Basin, Yemen. *Management of Environmental Quality: An International Journal* **16** (4), 347–361.
Naidu, C. R. & Giridhar, M. V. S. S. 2011 Geo-spatial database creation for Wazirabad canal command area. *Geographical Information Systems* **3** (4), 290–297.
Nixon, J. B., Dandy, G. C. & Simpson, A. R. 2001 A genetic algorithm for optimizing off-farm irrigation scheduling. *Journal of Hydroinformatics* **3** (1), 11–22.
Ortega, J. F., Juan, J. A. & Tarjuelo, J. M. 2005 Improving water management: the irrigation advisory service of Castilla-La Mancha (Spain). *Agricultural Water Management* **77** (1), 37–58.

Pervez, M. S. & Hoque, M. A. 2008 Interactive information system for irrigation management. *Pergamon, Physics and Chemistry of the Earth* **28**, 927–934.

Rao, N. H., Brownee, S. M. & Sarma, P. B. 2004 GIS-based decision support system for real time water demand estimation in canal irrigation systems. *Current Science* **87** (5), 628–636.

Raut, A. K., Bansal, A. K., Verma, V. K. & Marr, A. J. 2008 GIS-based decision support system for conjunctive irrigation management in India. In: *11th International River Symposium*, Brisbane, Australia (1–4 September 2009).

Ray, S. S. & Dadhwal, V. K. 2001 Estimation of crop evapotranspiration of irrigation command area using remote sensing and GIS. *Agricultural Water Management* **49** (3), 239–249.

Ray, S. S., Dadhwal, V. K., Chhabra, S. B. & Brahmabhatt, V. S. 2000 Application of remote sensing and geographic information systems in irrigation management of Mahi command area in Gujarat, India. *NNRMS Bulletin*, DOS, Bangalore, 25, 17–21.

Ray, S. S., Dadhwal, V. K. & Navalgund, R. R. 2002 Performance evaluation of an irrigation command area using remote sensing: a case study of Mahi command, Gujarat, India. *Agricultural Water Management* **56** (2), 81–91.

Su, M. D. & Wen, T. H. 2001 Spatial decision system for irrigation demand planning. In: *Bridging the GAP: Meeting the World's Water and Environmental Challenges, Proceedings of the World Water and Environmental Resources Congress, 20–24 May 2001, Orlando, FL*, D. Phelps & G. Sehlke (eds), ASCE, EWRI.

Suresh Babu, A. V., Shanker, B. M. & Rao, V. V. 2012 Satellite derived geospatial irrigation performance indicators for benchmarking studies of irrigation systems. *Advances in Remote Sensing* **1**, 1–13.

Suryavanshi, A. R. & Reddy, J. M. 1986 Optimal operation schedule of irrigation distribution systems. *Agricultural Water Management* **11** (1), 23–30.

Sheate, W. R., Eales, R. P., Daly, E., Baker, J., Murdoch, A., Hill, C., Ojike, U. & Karpouzoglou, T. 2012 Spatial representation and specification of ecosystem services: a methodology using land use/land cover data and stakeholder engagement. *Journal of Environmental Assessment and Policy Management* **14** (1), 1250001.

Tabari, H., Trajkovic, S. & Grismer, M. E. 2013 Comparative analysis of 31 reference evapotranspiration methods under humid conditions. *Irrigation Science* **31** (2), 107–117.

Teixeira, J. L. & Pereira, L. S. 1992 ISAREG, an irrigation scheduling model. *ICID Bulletin* **41** (2), 29–48.

Todorovic, M. & Steduto, P. 2003 A GIS for irrigation management. *Physics and Chemistry of the Earth* **28** (4), 163–174.

Tsihrintzis, V. A., Hamid, R. & Hector, R. F. 1996 Use of Geographic Information Systems (GIS) in water resources: a review. *Water Resources Management* **10** (4), 251–277.

Yamashita, S. & Walker, W. R. 1994 Command area water demands I: validation and calibration of UCA model. *Journal of Irrigation and Drainage Engineering* **120** (6), 1025–1042.

Yoo, S. H., Choi, J. Y. & Jang, M. W. 2008 Estimation of design water requirement using FAO Penman–Monteith and optimal probability distribution function in South Korea. *Agricultural Water Management* **95** (7), 845–853.

First received 6 December 2015; accepted in revised form 26 April 2016. Available online 6 May 2016