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A climatic water balance model 'WatBal' for bio-climatic classification and agro-climatic analysis

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ABSTRACT

A computer software (WatBal) was developed for estimating climatic water balance components and length of growing period (LGP) for individual stations using overhead climatic data and soil water retention. The program computes various components of water budget (water surplus/deficit, humidity/aridity/moisture indices, bio-climatic type) following the standard methods considering precipitation (P), potential evapotranspiration (PET), and available water holding capacity (AWC) of soils as inputs at either monthly or weekly time steps. The essential inputs for the program are rainfall and evapotranspiration. Mean rainfall is derived from climatic normals and the evapotranspiration is estimated following Penman-Monteith relation based on inputs of normal temperature, humidity, radiation parameters specific to a location. The water-balance program tested for many stations with diverse soil, physiography and climate conditions over India and was found to provide good results. Spatial interpolation techniques in Geographical Information System (GIS) have been adopted for interpretation of geographical variation of the various water budget components. The WatBal software was used in many agriculture research areas in India. A few applications viz., delineation of bio-climatic types, crop growing period, delineation of agro-ecological regions/sub-regions, agricultural drought classification are discussed.

Key words : *Water balance, Growing period, Bio-climate*

Introduction

Bio-climate and crop growing period are essential parameters in land evaluation, agriculture resource management and efficient crop planning. Several agricultural research programs in India were designed based on the application of soil–climatic water balance (Sehgal *et al*., 1992). Water balance procedure is highly useful in the determination of crop water requirements, classification of bio-climate and for hydrological calculations of river water basins (Subrahmanyam, 1983). Estimations of water budgeting are tedious especially when the time step is over weekly periods and when a large number of locations are involved. Several computer codes exist for estimating the water balance mainly for hydrological applications. Westenbroek *et al.,* (2010) have developed a computer code called Soil-Water-Balance (SWB) for ground water application. Similarly ENWATBAL was developed to compute soil and crop evapotranspiration as a function of crop development and weather through numerical modeling of energy and waterbalances of soil-plant-atmosphere system (Evett and Lascanno, 1993). Some of these codes have been internationally used towards specific applications. For example, Meenakshi *et al*

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(2007) have evaluated the capability of HR Wallingford and Cranfield University, UK jointly developed the Water Simulation model, WaSim (Hess *et al.,* 2000) to predict the ground water behavior for varied drainage conditions in the semi-arid region of Haryana in India. Anuraga *et al.,* (2006) used a one-dimensional agro-hydrological model soil–water–atmosphere–plant (SWAP) (Van Dam *et al.,* 1997; Kroes *et al.,* 1999) in conjunction with a geographical information system to assess the effect of land use and soil on groundwater budgets at the subwatershed scale. Although many softwares for water balance computation exist they are tailored suitable for specific applications and each with specific data requirements and formats. For example ENWATBAL is developed mainly for estimating crop water requirements of specific crops, therefore requires a vast number of inputs in evaluating the surface energy balance and evapotranspiration. In a macroscale application many of the fine details of the crops, energy balance can be simplified in terms of simple inputs on evapotranspiration, rainfall, soil textrure, derived at station level using micrometeorological observations and soil survey maps. Growing period, bio-climatic classification, agro-eco zonation of large areas are some typical examples where a simplistic water balance approach is sufficient to assess the eco-conditions needed in agriculture planning. However, even simple water balance calculations at monthly or weekly time scales over specific stations require handling large amount of climatic data and soil details. In the present work, to facilitate easy and faster computations of water balance for a large number of stations needed in bio-climatic classification and agro-eco zoning a computer code was developed. The software was developed in Visual Foxpro and tested with climatic data on rainfall, evapotranspiration from India Meteorological Department (Rao *et al.,* 1971) and soil data from the National Bureau of Soil Survey and Land Use Planning (NBSS & LUP), India. The code is written in Microsoft Visual Foxpro for estimation of water balance on monthly/weekly time steps. In this paper the development of the WatBal software for water balance and growing period estimation is described along with some of its significant applications. A brief description of the methods of water balance and growing period estimations are given sections 2, followed by brief description of the software in section 3, and some of the salient applications in section 4.

Methods of Calculation of Water Balance and Growing Period

Soil-climatic water balance is a budget of water received geographically at any given location by rainfall and other precipitation processes and the loss of water due to evapotranspiration, runoff, and water storage in the soil medium (Subrahmanyam, 1983). It is a balance between the water need and water supply. The potential evapotranspiration (*PET*) is the combined loss of water by evaporation and transpiration from a vegetated soil surface with adequate moisture supply and is a function of temperature and day length. When rainfall equals the water need, the total amount of available water from rainfall is consumed for evapotranspiration and the soil moisture remains at its level. When the water supply (by rainfall) exceeds the water need, part of it infiltrates in to the soil for recharging. When the soil water reaches its capacity called Available Water Holding Capacity (*AWC*), the excess water from rain percolates to the deeper layers and is considered as water surplus. Part of this water surplus will be utilized for ground water recharge and the rest runs off to the rivers. When the water supply is less than the water need, the water from the soil moisture is drawn up by the roots for evapotranspiration until the wilting point is reached. If the water need cannot be met from stored soil moisture a water deficit will occur. When the water supply is not adequate, transpiration progresses at a reduced rate. The water storage by soil medium is a function of the water holding capacity of the soil catena which is dependent on the soil physical properties such as texture, bulk density, porosity and the depth of the soils.

The procedure adopted in the computation of water balance and growing period in the software is described below:

Estimation of Climatic Water Balance

The water budget estimations are made following Thornthwaite and Mather (1955) and Subrahmanyam (1983). The water balance equation is solved in monthly and weekly time steps to evaluate the water deficit (*WD*) or water surplus (*WS*) components.

$$P - ET - \Delta S - R = 0 \quad .. (1)$$

Where P is the rainfall, *ET* is the evapotranspiration, *DS* is the change in the soil moisture due to depletion by evapotranspiration or infiltration of water by precipitation and *R* is the runoff. The release of soil moisture 'S' is an exponential function.

$$S = AWCe^{APWL/AWC} \quad .. (2)$$

AWC is the storage capacity of the soil moisture, accumulated potential water loss (*APWL*) is accumulated values of (*P-ET*)<0 up to the month or week considered, which is always negative. The actual evapotranspiration (*AET*) is estimated as *DS+P* when *DS* is positive and *ET* when *DS* is negative. The deficit is treated as *ET-AET*. The water surplus is treated as *(P-ET)-DS* which is the water available above the storage capacity of soil that percolates to the water table and becomes available for runoff to the underground system.

The main application of water balance is to assess the bio-climatic indices and growing period of crops. The climatic indices can be determined from annual water surplus, annual water deficit and their difference. The climatological indices viz., humidity index (*Ih*), ariditiy index (*Ia*) and the moisture index (*Im*) on annual basis are computed as

$$Ih = \frac{WS}{ET} x100 \quad .. (3)$$

$$Ia = \frac{WD}{ET} x100 \quad .. (4)$$

$$\mathrm{Im} = Ih - Ia \quad .. (5)$$

The Moisture Adequacy Index (*MAI*) for each week are calculated (for weekly data only) using the formulae *MAI = (AET/PET)x100*. Runoff to the drainage system is estimated from the water surplus on the assumption that half the surplus from the previous month/week is available for runoff in the next time step. The available water capacity for dominant soil (covering atleast 50% or more in a given soil unit) is approximated from depth of soil, texture of control section of soil, presence of gravel and dominant soil mineralogy (Sehgal *et al.*, 1992). The bio-climate of any location is defined using the aridity index, humidity and moisture indices as per the Thornthwaite and Mather procedure.

Estimation of Length of Growing Period (LGP)

Length of Growing Period (LGP) is the period when soil moisture is adequate enough to support plant growth and is a parameter defined mainly for rainfed crops. LGP starts when precipitation exceeds 0.5 potential evapo-transpiration (MAI >50) and ends with utilization of stored moisture, i.e. 0.25 PET (MAI>25) (Higgins and Kassam, 1981). Growing period varies according to climate (rainfall, temperature, radiation etc) as well as the nature of soils (through water holding capacity). Provision for calculating LGP using software was provided for weekly data only. However, calculation of LGP for monthly data sets is facilitated through importing the data file in Microsoft excel and through plotting the graph considering rainfall (P), potential evapotranspiration (PET), actual evapotranspiration (AET). LGP is an important parameter used to judge the agricultural potential and for delineating agro-ecological regions (FAO, 1983; Sehgal *et.al.,* 1992). In India rainfall occurs mainly in two seasons i.e. South West Monsoon (June-September) and North East Monsoon (October-December). Accordingly we have two crop growing seasons, i.e. *kharif* (June-September/October) and rabi (September/October-December/January) slightly extended beyond rainy seasons based on moisture storage capacity of soils.

Description of Software

The software was developed using Microsoft Visual Foxpro 9.0 programming language. The outputs of the software can be plotted either as time series water balance graphs for individual stations or as spatial maps using interpolation techniques in Geographical Information System. The software architecture of WatBal and the GIS techniques for interpolation of outputs are described below.

Data Management and program structure

Data management has been designed to create input file in dBase (.dbf) format. The database file contains 3 input fields (rainfall (*P*), potential evapotranspiration (*PET*) and available water capacity (*AWC*) and 7 calculated fields (water excess/deficit (*P-PET*), accumulated potential water loss (*APWL*), storage (*ST*), storage difference (*DS*), actual evaporation (*AET*), water deficit (*WD*) and water surplus (*WS*)). Fig. 1 gives the generalized flow chart depicting the water balance estimation.

Fig. 2 shows the main menu of the software. It has a data input module (Entry), data editing module (Edit), data print module (Print) for both monthly and weekly time steps. The essential inputs are given either as monthly or weekly inputs in mm. The data input module for monthly/weekly data

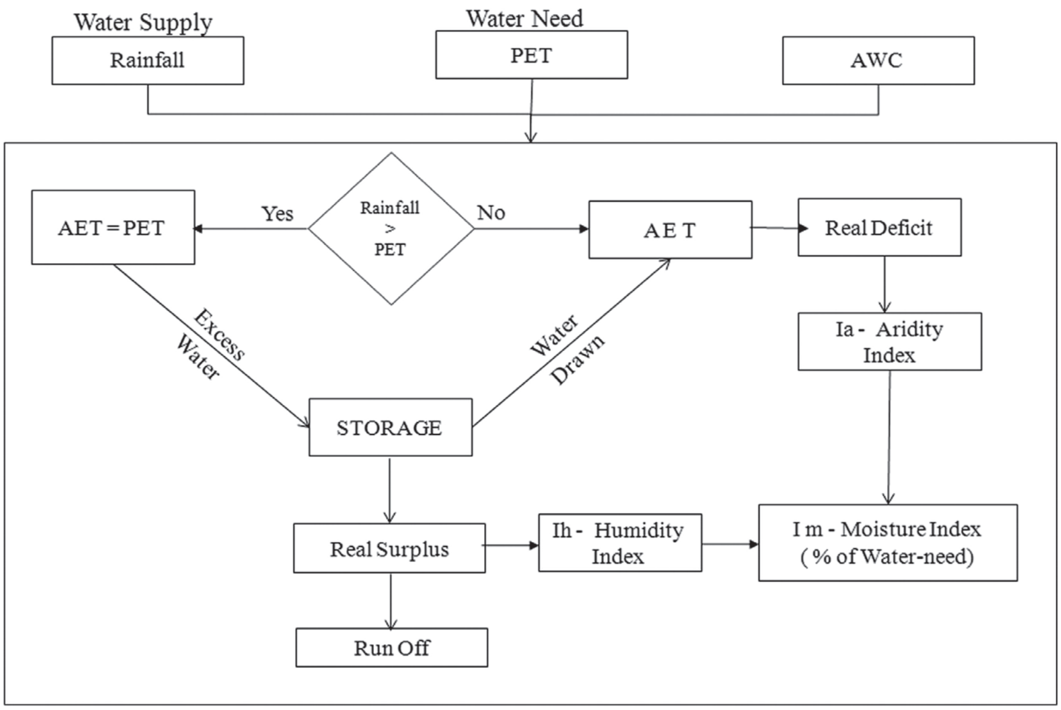


Fig. 1. Schematic diagram of water balance procedure used for individual stations

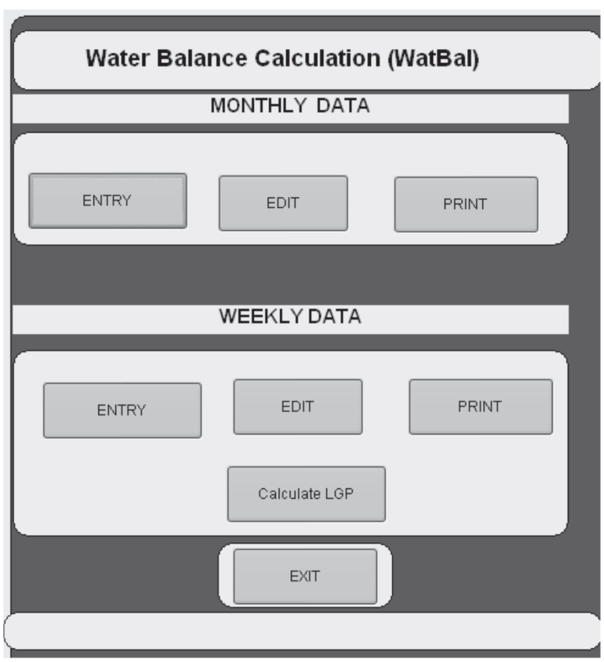
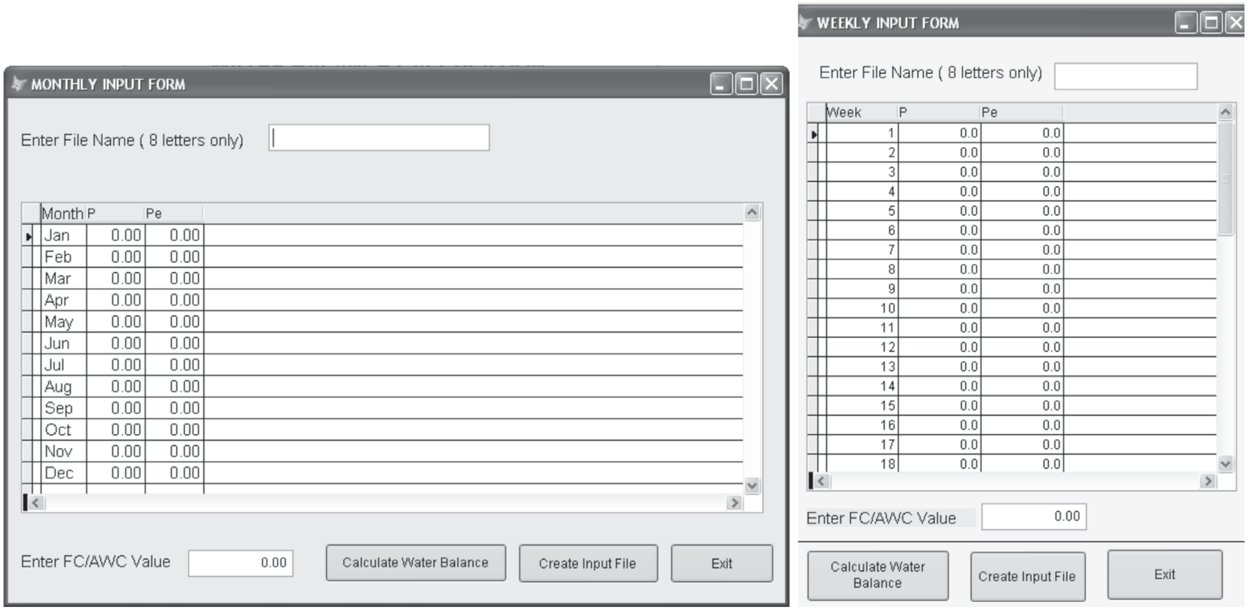


Fig. 2. The front end of the water-balance software

sets are illustrated in Fig. 3. Based on the selection of either monthly or weekly calculation option, the user will be presented with the screen for data entry (Fig. 3). In the data entry screen the user can enter *P*, *PET* and *AWC*. This screen facilitates calculation of water balance and printing the results in a standard form as shown in by selecting options for either monthly or weekly data (Fig. 4). Fig. 5 shows the water balance diagram of Dharmapuri, Tamil Nadu, as an example, prepared using the resultant file in MS Office Excel application.

Spatial Mapping of Water Balance Components and LGP

An important application of water balance software is to assess the water balance parameters for larger regions of interest at eco-system level. The techniques of Spatial or Polynomial Interpolation available in Geographical Information System (GIS) were adopted to obtain spatial maps of the water balance components. The SPANS (Spatial Analysis System) (SPANS, 1997) was used for this purpose. The water balance components can be linked with latitude and longitude of each station and can be compiled into standard database format (.dbf files). The database file with parametric data of a large number of stations was imported in SPANS GIS in a suitable earth geographic projection. Triangulated irregular network (TIN) when applied to the data points creates a grid of points based on the spatial density of the



(a) (b)

Fig. 3. Data entry screen for a) monthly data b) weekly data

WATER BALANCE

STATION : Dharmapuri, Tamil Nadu

LAT : 12.13

LONG : 78.163

Month	P	PET	AWC	P-PET	APWL	Stor	DS	AET	WD	WS
Jan	3.40	85.70	100.00	-82.30	-142.90	23.95	-30.60	34.00	51.70	0.00
Feb	2.60	109.00	100.00	-106.40	-249.30	8.27	-15.68	18.28	90.72	0.00
Mar	21.10	160.10	100.00	-139.00	-388.30	2.06	-6.21	27.31	132.79	0.00
Apr	53.20	178.30	100.00	-125.10	-513.40	0.59	-1.47	54.67	123.63	0.00
May	96.10	186.90	100.00	-90.80	-604.20	0.24	-0.35	96.45	90.45	0.00
Jun	66.00	171.80	100.00	-105.80	-710.00	0.08	-0.16	66.16	105.64	0.00
Jul	78.50	159.60	100.00	-81.10	-791.10	0.04	-0.04	78.54	81.06	0.00
Aug	103.90	158.10	100.00	-54.20	-845.30	0.02	-0.02	103.92	54.18	0.00
Sep	211.90	150.80	100.00	61.10	0.00	61.12	61.10	150.80	0.00	0.00
Oct	151.30	142.30	100.00	9.00	0.00	70.12	9.00	142.30	0.00	0.00
Nov	81.90	99.60	100.00	-17.70	-17.70	83.78	13.66	95.56	4.04	0.00
Dec	28.10	71.00	100.00	-42.90	-60.60	54.55	-29.23	57.33	13.67	0.00

IH 0.0000 IA 44.6976 MI -44.6976

CLIMATIC CLASSFICATION : D2 d A` a`

Semi-arid (semi-dry), Small or no Seasonal Water

Fig. 4. Typical results of water balance calculation

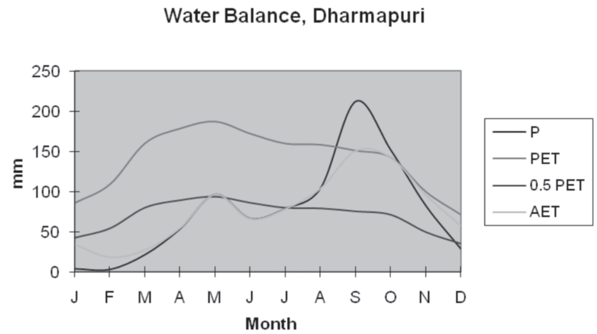


Fig. 5. Water balance diagram

data points (Burrough, 1986). Among several interpolation techniques available such as inverse distance, krigging (spherical, ellipsoid), bilinear, voronoi, thespian polygons etc., the inverse distance method was used in the present work for its simplicity and reasonable accuracy.

Applications of Water Balance in agro-climatic analysis

Water balance procedure is one of the widely used concepts in climatology and agricultural crop planning. In India the program was rigorously used in various projects viz., determination of Bio-Climatic Types, Agro-Ecological Regions/ Sub-regions, determination of Crop Growing Period, Drought assessment etc. Here, the utility of the program in agricultural planning applications for Andhra Pradesh is presented in the following sections.

Agro-Ecological Zones

Crop planning requires detailed knowledge on the prevailing agro-climatic conditions, nature of soils and their spatial distribution in a given region. Grouping of similar soil agroenvironments is essential for conducting agricultural research, transfer of technology and regional planning for sustainable use of natural resources. This necessitates proper analysis and interpretation of soils and climatic data. Agroclimatic zone is a land unit in terms of major climate suitable for a range of crops and cultivars (FAO, 1983) whereas an agroecological zone is a land unit within an agroclimatic zone having distinct kind of soils with specific length of growing period. The agro-ecological zone is a basic unit to disseminate research results and agricultural technology to other similar soil-agro-environments. It helps to determine the suitability of different crops for regional developmental purposes. The state of Andhra Pradesh receives rainfall from south-west monsoon in the northern and central parts and mostly from northeast monsoon in the extreme south and southeast coastal plains. The soils are also highly variable geographically. These diverse conditions influence the cropping patterns. The earliest attempt in agroclimatic classification of Andhra Pradesh was by Subramanyam and Subramaniam (1962) who divided the State into 4 climatic zones. The Andhra Pradesh Agricultural University has divided the State into 7 agroclimatic zones under National Agricultural Research Project (NARP) for generation and dissemination of agrotechnology. The agricultural research and farming technologies being conducted and recommended in the State were based on 7 agro-climatic zones as adopted by the Agricultural University and the Department of Agriculture. Here the application of the water balance program for the agro-ecological zoning of Andhra Pradesh State is illustrated wherein the available soil resource mapping data and climatic data have been used (Naidu *et al.,* 1998).

Long-term weekly rainfall data (1969-93) of 700 provincial raingauge stations obtained from India Meteorological Department, Pune were used for the study. The soil resource information generated on 1:250,000 scale for the State (Reddy *et al.,* 1996) was used to derive the soil types. The available water capacity at 50, 75, 100, 150, 175 and 225 mm/meter depth of soil were assigned based on soil depth, texture, gravel content and mineralogy of soils. The available water capacity values were assigned to all the soils studied at 2740 grid points located at 10 km interval. The potential evapotranspiration data was obtained from IMD bulletin (Rao *et al.,* 1971). With the inputs of AWC, weekly rainfall and potential evapotranspiration data, the soil water balance software was run to assess the length of growing period and using GIS software LGP map was prepared. The LGP map was superimposed over soil and physiography layer maps through GIS and a 22 agro-ecological zones map was generated. The latter depicted agrosoilenvironments in the State with unique physiography, climate, soils and length of growing period. The 22 AEZ units forms homogeneous management units for use and conservation of natural resources for higher productivity.

Drought assessment in Karnataka State

The traditional methods of assessing agricultural droughts are based on parameters such as rainfall which have limitations in spatially delineating their extent and severity (Venkataraman, 2003; Irrigation Commission, 1972) within an administrative unit such as a district. The severity of drought can vary according to the type of vegetation, types of soils as well as the variability in spatial distribution of rainfall itself. Since LGP represents the duration of favorable moisture availability based on rainfall, evaportranspiration, soil moisture it can be taken as index of agriculture drought. Using the above approach Naidu and Srinivas (2005) studied the drought prone areas in Karnataka state. For the drought analysis weekly rainfall data (1980-2001) of 175 locations, potential evapo-transpiration and major soil types covering the entire State were used. Using the Water Balance program the LGP for each location was determined for all 22 years, and grouped into 5 classes of growing period i.e. < 90 days, 90-120 days, 120-150 days, 150-180 days and > 180 days. Each location was assigned with length of growing period class that has repeated maximum number of years out of 22 years. The areas that experience with LGP <90 days were classified as chronically drought prone, 90-120 days LGP as severely drought prone, 120-150 days LGP as moderately drought prone, 150-180 days LGP as mild and > 180 days LGP as rarely drought prone.

Summary and Conclusion

A computer software 'WatBal' is developed for Soil Water balance and Growing Period estimations based on the standard methods. The program handles the climatic data sets either at monthly or weekly time intervals and facilitates evaluation of water balance components as well as growing period for a large number of stations. The program found large utility in various agro-climatological applications like delineation of Agro-Ecological Regions/Sub-regions of India and its different states, drought assessment and bio-climate classification. The program was extensively used to assess water balance estimations for about 2000 stations in India in a reasonable time frame with desired accuracy enabling to generate details on the bio-climate, growing period for the delineation of AER/AESR at national level. Presently the program uses the data on evapotranspiration as an input which is either estimated outside the program or taken directly from available reports. The value of PET is likely to vary at different locations depending on the site specific parameters of radiation, temperature, humidity and hence needs to be estimated precisely following the Penman method (PET, Penman, 1948). It is known that the bio-climate indices are sensitive to the inputs of precipitation, evapotranspiration data which are expected to have a natural variation according to varying climate. The program therefore finds potential application in regional climate change studies and the related scenario assessments.

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References

Anuraga, T.S., Ruiz, L., Mohan Kumar, M.S., Sekhar, M. and Leijnse, A. 2006. Estimating groundwater recharge using land use and soil data: A case study in South India. *Agricultural Water Management*. 84 : 65-76.

Burrough, P.A. 1986. *Principles of Geographical Information Systems for Land Resource Assessment. Monographs on Soil and Resources Survey*. Clarendon Press, Oxford. pp. 193.

Evett, S.R. and Lascano, R.J. 1993. ENWATBAL.BAS: A Mechanistic Evapotranspiration Model Written in Compiled BASIC. *Agronomy J.* 85 (3) : 763-772.

FAO, 1983. Guidelines: Land Evaluation of Rainfed Agriculture. *Soils Bulletin*. 52, *FAO*, Rome, Italy, 237 pp.

Hess, T.M., Leeds-Harrison, P. and Counsell, C. 2000. WaSim Manual. Institute of Water and Environment, Cranfield University, Silsoe, UK (2000).

Higgins, G.M. and Kassam, A.H. 1981. The FAO Agroecological zone approach to determining of land potential. *Pedologie*. XXXI, 2 : 147 168.

Irrigation Commission, 1972. Ministry of Irrigation and Power, Govt. of India Vol. 1, New Delhi P-160.

Kroes, J.G., Van Dam, J.C., Huygen, J. and Vervoort, R.W. 1999. User's Guide of SWAP Version 2.0. Simulation of water ow, solute transport and plant growth in the Soil–Water–Atmosphere–Plant environment. Technical Document 48, Alterra Green World Research, Wageningen, Report 81, Department of Water Resources, Wageningen University and Research, Wageningen, The Netherlands, 127 pp.

Meenakshi, H., Gupta, S.K. and Mishra, K.L. 2007. Application of WaSim to assess performance of a subsurface drainage system under semi-arid monsoon climate. *Agricultural Water Management*. 88 : 1–3 : 224–234.

Naidu, L.G.K., Reddy, R.S., Sah, K.D., Bhaskar, B.P., Datta, D., Niranjana, K.V., Dhanorkar, B.A., Srinivas, S., Nagaraju, M.S.S., Ray, S.K., Raghumohan, N.G., 1998. Mapping of agroecological zones of Andhra Pradesh through soil-resource data. *Indian Journal of Agricultural Sciences.* 68 (10) : 661-5.

Naidu, L.G.K. and Srinivas, S. 2005. Length of growing period as a criteria for identifying different drought types in Karnataka. *Indian Journal of Agricultural Sciences.* 75 (9) : 614-5.

Penman, H.L. 1948. Natural evaporation from open water, bare soil and grasses, *proc. Roy. Soc. London (Series A)*, 193, 120-145.

Reddy, R. S., Shiva Prasad, C. R. and Harindranath, C. S. 1996. Soils of Andhra Pradesh for Optimising Land Use, Publication 69, National Bureau of Soil Survey and Land Use Planning, Nagpur.

Rao, K.N., George, C.J. and Ramashastri, K.S. 1971. Potential Evapotranspiration over India, IMD Report No. 36, Pune, 7p.

Sehgal J., Mandal, D.K., Mandal, C., Vadivelu, S. 1992. Agro-Ecological Regions of India, *NBSS Publ. 24*, Technical bulletin, National Bureau of Soil Survey and Land Use Planning, Nagpur (India).

SPANS., 1997. Spatial Analysis System. Manual of SPANS. Ver. 7.0, Language Reference, pp.1-107, Tydac Research Inc., Ontario, Canada.

Subrahmanyam, A.R. 1983. Agro-ecological Zones of India. *Arc. Met. Geoph. Boocl. Ser B.* 32 : 329-333.

Subrahmanyam, V.P. 1983. Water Balance and Its Applications in Agriculture. *Meteorological Monogarpah.*, Andhra University Press, Visakhapatnam, 133 pp.

Subrahmanyam, V.P. and Subramaniam, A.R. 1962. Climatic features of Andhra Pradesh. *Journal of Indian Society of Soil Science.* 10 (2) : 128-153.

Thorthwaite, C.W. and Mather, R.J. 1955. The Water Balance Publication in Climatology 8(1), DIT, Laboratory of climatology, Centerton, NJ 104 p.

Venkataraman, S. 2003. Agrometerological aspects and assessment of proneness to crop droughts. *Journal of Current Science.* 3 (2): 301-304.

Van Dam, J.C., Huygen, J.,Wesseling, J.G., Feddes, R.A., Kabat, P.,VanWalsum, P.E.V., Groenendijk, P., Van Diepen, C.A. 1997. Theory of SWAP Version 2.0. Simulation of Water Flow, Solute Transport and Plant Growth in the Soil–Water–Atmosphere–Plant Environment. Report 71, Department of water resources, WAU, Technical Document 45, DLOW inand Staring Centre DLO, 167 p.

Westenbroek, S.M., Kelson, V.A., Dripps, W.R., Hunt, R.J., Bradbury, K.R. 2010. SWB- A Modified Thronthwaite-Mather Soil-Water-Balance Code for Estimating Groundwater Recharge. U.S. Geological Survey. *Techniques and Methods.* 6-A31, 60 p.