DRY FARMING

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Dry farming is cultivation of crops in regions with annual rainfall less thsan 750mm. Crop failure is most common due to prolonged dry spells during crop period. These are arid regions with a growing season (period of adequate soil moisture) less than 75 days. Moisture conservation practices are necessary for crop production. Dry farming constitutes about 67 per cent of the total cropped area of 142 M ha in the country contributing to about 42 per cent of total food production. Almost all the coarse grains and about 85 per cent of pulses and oilseeds com from dry farming. Dry farming may be practiced in areas that have significant annual rainfall during a wet season, often in the winter. Crops are cultivated during the subsequent dry season, using practices that make use of the stored moisture in the soil. California, Colorado and Oregon, in the United States, are three states where dry farming is practiced for a variety of crops.

Even after the utilisation of all water resources for irrigation, about half of the cultivated area will remain rainfed. As there is hardly any scope for increasing the area under cultivation, it is really a colossal task for meeting the future food needs. It is against this background that dry farming gained importance. In dry farming emphasis is on soil and water conservation, sustainable crop yields and limited fertiliser use according to soil moisture availability.

8. 1. HISTORY OF DRY FARMING

First systematic scientific approach to tackle the problems of dry farming areas was initiated by Tamhane in 1923 on small plots of Manjari farm near Pune and the work passes on to Kanitkar in 1926. A comprehensive scheme of research was drawn up by Kanitkar with financial support from ICAR. Realising the importance, the ICAR launched a comprehensive project on dryland farming in five centres: Sholapur and Bijapur in 1933. Hagari and Raichur in 1934 and Rohtak in 1935. A decade of work upto 1943-44 mainly on rainfall analysis, physico-chemical properties of soils, physiological studies in millets and on agronomic aspects resulted in series of dry farming practices commonly known as the Bombay dry farming practices. Hydrabad dry farming practices and Madras dry farming practices. These practices stressed the need for contour bunding, deep ploughing, application of FYM, low seed rate with wide spacing, mixed cropping and crop rotation. These recommendations could not motivate the farmers to adopt them as the yield advantage was about 15-20 per cent over a base yield of 200- 400 kg ha^{-1}

By the mid 1950s, importance of soil management was realised for improving the productivity of drylands and the ICAR established eight Soil Conservation Research Centres in 1954. However, yield improvement was not more than 15-20 per cent over the basic yield of 200-400 kg ha^{-1} . importance of short duration cultivars maturing within adequate soil moisture available period (crop growing period) was recognised during 1960s. The place of high yielding varieties and hybrids for yield advantage in dryland agriculture was realised in mid – 1960s. With the establishment of All India Coordinated Research Project for Dryland Agriculture (AICRPDA) IN 1970, emphasis was shifted to multi- disciplinary approach to tackle the problem from several angles. Similar efforts wee initiated at ICRISAT, Hyderabad in 1972. The ICAR selected 23 dryland agricultural centres all over the country on basis of the moisture deficit, soil type and rainfall characteristics.

Major events in dryland agriculture research are:

1920	Scarcity tract development given importance by Royal Commission on Agriculture
1923	Establishment of Dry Farming Research Station at Manjiri
1933	Research Stations established at Bijapur and Shilapur
1934	Research Stations established at Hagari and Raichur
1935	Research Station established at Rohtak
1942	Bombay Land Development act passed
1944	Monograph on dry farming in India by Kanitkar
1953	Establishment of Central Soil Conservation Board
1955	Dry Farming Demonstration Centres started
1970	Twenty three Research Centres established under AICRPDA
1972	Establishment of ICRISAT
1976	Establishment of dryland Operational Research Projects (ORPs)
1977	Krishi Vigyan Kendra (KVK), Hyatnagar
1983	Starting 47 model watersheds under ICAR
1984	Establishment of Dryland Development Board in Karnataka and World Bank Assisted Watershed Development Programmes in four states
1985	Central Research Institute for Dryland Agriculture (CRIDA), Hyderabad
1986	The NWDPRA programmes in 15 states by Government of India

8. 2. PROBLEMS OF DRY FARMING

In India, the problem of crop production in drylands are more numerous and varied as it is practiced under a wide range of climate and soil conditions. These problems can be broadly grouped into three: vagariesof monsoon, soil constraints and socio- economic.

8.2.1 Vagaries of Monsoon

Based on average annual rainfall, the country can be divided into three zones: low (less than 750 mm), medium (750-1,150 mm) and high (more than 1,150 mm)rainfall zones. Dryland area is nearly equally distributed among the three. Areas with less than 1,150 mm (arid and semi-arid) are the problem areas for crop production. Main characteristics of rainfall influencing crop production are its variability, intensity and prolonged dry spells during the crop period.

8.2.2 Soil Constraints

Alluvial soils occupy the largest area in dryland agriculture. Problems of crop production are not so acute in these soils as they are in black and red soils. Major problems are encountered in Vertisols, Alfisols and related soils. Black and red and associated soils are mostly distributed in central and south India. The coastal area have Alfisols, laterite and lateritic soils.

8.2.3. Socio- Economic Constraints

The socio-economic status of dryland farmers, generally, will not permit them in adopting the recommended dryland technology. Major socio-economic constraints are:

- Lack of capital, support price for the produce, marketing and credit facilities make the farmers hesitate to invest on recommended technology

- Most of the resource poor family opt for avoiding risk in dryland agriculture
- Poor agricultural structure for input supply in dryland areas

8. 3. STRATEGY FOR DRY FARMING

Any technology for drylands should be able to maximise the benefits of a good season and minimise the adverse effects of an unfavourable season. Attempts were made to develop a good weather code and drought code. When the monsoon is normal, it should be used most effectively, using a best variety and the recommended package of practices.

Drought code come into operation with aberrant weather and the drought programmes indicate:

- Maximising production through alternate cropping pattern
- Midseason correction to standing crops
- Crop life saving irrigation
- Build up of seed and other inputs to implement the drought complex strategies

Measures necessary for counteracting aberrant weather:

- Thinning the plants or rows in a sole crop
- Removal of the most sensitive croop in intercropping system
- Ratooning on receipt of rain if the damage is not beyond recovery
- Sowing a new crop suitable to the remaining part of the season
- Urea spray
- Life saving irrigation

8. 4 MOISTURE CONSERVATION IN DRYLANDS

Annual rainfall in several parts of drylands is sufficient for one or more crops per year. Erratic and high intensity storms leads to runoff and erosion. The effective rainfall may be 65 per cent or sometimes less than 50 per cent. Hence, soil management practices have to be tailored to store and conserve as much rainfall as possible by reducing the runoff and increasing storage capacity of soil profile. A number of simple technologies have been developed to prevent or reduce water losses and to increase water intake

8.4.1 Tillage

The surface soil should be kept open for the entry of water through the soil surface. Offseson shallow tillage aids in increasing rain water infiltration besides decreasing weed problems. Deep tillage once in 2 to 3 years have extremely beneficial in shallow red soils of Anantapur (AP). Contour cultivation is effective in reducing soil and water loss. On red soils, crusting is a serious constraint to seedling emergence and soil and water conservation. Shallow tillage during initial stage of crop with inter cultivation implements will be effective in breaking up the crust and improving filtration. Unfortunately, all the tillage practices that increase entry of water also tend to increase evaporation losses from surface soil. This is the major component of storage inefficiency in soils with high water holding capacity

8.4.2 Fallowing

Traditional dryland cropping system of deep vertisols involve leaving the land fallow during rainy season and raise crops only during post rainy season on profile stored stored moisture. The main intention of fallowing is to provide sufficient moisture for the main post rainy season crops. The monsoon rains, even in drought years, usually exceeds storage capacity of root zone soil depth. This system probably provides some level of stability in the traditional system, though in years of well distributed rainfall, the chance of harvesting good crop is lost. Probably poor drainage, tillage problems and weed control have forced the farmers to adopt post rainy season cropping. Sice the soil has to be kkept weed free during rainy season, the problem of erosion and runoff increases considerably.

8.4.3 Mulching

Mulching is a practice of covering soil surface with organic materials such as straw, grass, stones, plastics etc, to reduce evaporation to keep down weeds and also to moderate diurnal soil temperatures. Soil and runoff losses can also be reduced considerably. The effectiveness of mulches in conserving moisture is relatively higher under conditions of more frequent rains, drought and during early plant growth when canopy cover remains scanty. Though, mulches are useful in mitigating moisture stress effects, availability and cost is limiting their use.

8. 5. DRY FARMING PROCESS

Dry farming depends on making the best use of the "bank" of soil moisture that was created by winter rainfall. Some dry farming practices include:

- Wider than normal spacing, to provide a larger bank of moisture for each plant.
- Controlled Traffic.
- Minimal tilling of land.
- Strict weed control, to ensure that weeds do not consume soil moisture needed by the cultivated plants.
- Cultivation of soil to produce a "dust mulch", thought to prevent the loss of water through capillary action. This practice is controversial, and is not universally advocated.
- Selection of crops and cultivars suited for dry farming practices.

Capturing and conservation of moisture

In regions such as Eastern Washington, the average annual precipitation available to a dryland farm may be as little as 8.5 inches (220 mm). Consequently, moisture must be captured until the crop can utilize it. Techniques include summer fallow rotation (in which one crop is grown on two seasons' precipitation, leaving standing stubble and crop residue to trap snow), and preventing runoff by terracing fields.

"Terracing" is also practiced by farmers on a smaller scale by laying out the direction of furrows to slow water runoff downhill, usually by plowing along either contours or keylines. Moisture can be conserved by eliminating weeds and leaving crop residue to shade the soil.

Effective use of available moisture

Once moisture is available for the crop to use, it must be used as effectively as possible. Seed planting depth and timing are carefully considered to place the seed at a depth at which sufficient moisture exists, or where it will exist when seasonal precipitation falls. Farmers tend to use crop varieties which are drought and heat-stress tolerant (even lower-yielding varieties). Thus the likelihood of a successful crop is hedged if seasonal precipitation fails.

Soil conservation

The nature of dryland farming makes it particularly susceptible to erosion, especially wind erosion. Some techniques for conserving soil moisture (such as frequent tillage to kill weeds) are at odds with techniques for conserving topsoil. Since healthy topsoil is critical to sustainable dryland agriculture, its preservation is generally considered the most important long-term goal of a dryland farming operation. Erosion control techniques such as windbreaks, reduced tillage or no-till, spreading straw (or other mulch on particularly susceptible ground), and strip farming are used to minimize topsoil loss.

Control of input costs

Dryland farming is practiced in regions inherently marginal for non-irrigated agriculture. Because of this, there is an increased risk of crop failure and poor yields which may occur in a dry year (regardless of money or effort expended). Dryland farmers must evaluate the potential yield of a crop constantly throughout the growing season and be prepared to decrease inputs to the crop such as fertilizer and weed control if it appears that it is likely to have a poor yield due to insufficient moisture. Conversely, in years when moisture is abundant, farmers may increase their input efforts and budget to maximize yields and to offset poor harvests.

REFRENCES

Adler, M.J., Busuioc, A., Ghioca, M., Stefan, S., 1999. Atmospheric processes leading to drought periods in Romania. In: Gottschalk, L., Olivoy, J.-C., Reed, D., Rosbjerg, D. (Eds.), Hydrological Extremes: Understanding, Predicting, Mitigating. IAHS Publication No. 255. IAHS Press, Wallingford, pp. 37–47.
Alegria, M.H., Watkin Jr., D.W., 2007. Annual and warm season drought intensity–duration–frequency analysis for Sonora, Mexico. J. Climate 20, 1897–1909.
Andreadis, K.M., Lettenmaier, D.P., 2006. Trends in 20th century drought over the continental United States. Geophys. Res. Lett. 33, L10403 10410.11029/ 12006GL025711.
Andreadis, K.M., Clark, E.A., Wood, A.W., Hamlet, A.F., Lettenmaier, D.P., 2005. Twentieth-century drought in the conterminous United States. J. Hydrometeorol. 6, 985–1001.
ASCE Task Committee on Application of Artificial Neural Networks in Hydrology, 2000. Artificial neural networks in hydrology. I. Preliminary concepts. J. Hydrol. Eng. 5 (2), 124–137.
Bacanli, U.G., Firat, M., Dikbas, E.F., 2009. Adaptive Neuro-Fuzzy Inference System for drought forecasting. Stoch. Environ. Res. Risk Assess. 23, 1143–1154.
Balling Jr., R.C., Goodrich, G.B., 2007. Analysis of drought determinants for the Colorado River Basin. Climatic Change 82 (1–2), 179–194. doi:10.1007/s10584-006-9157-8, 2007.
Banik, P., Mandal, A., Rahman, M.S., 2002. Markov chain analysis of weekly rainfall data in determining drought-proneness. Discrete Dyn. Nat. Soc. 7, 231–239.
Bardossy, A., Li, J., 2008. Geostatistical interpolation using copulas. Water Resour. Res. 44, W07412. doi:10.1029/2007WR006115.
Barnston, A., Glantz, M., He, Y., 1999. Predictive skill of statistical and dynamical climate models in SST forecasts during the 1997–98 El Ni~no episodes and the 1998 La Nina onset. Bull. Am. Meteorol. Soc. 80 (2), 217–242.
Barros, A.P., Bowden, G.J., 2008. Toward long-lead operational forecasts of drought: An experimental study in the Murray–Darling River Basin. J. Hydrol. 357 (3–4), 349–367.
Bates, B.C., Kundzewicz, Z.W., Wu, S. Palutikof, S. (Eds.), 2008. Climate change and water. Technical Paper of the Intergovernmental Panel on Climate Change, IPCC Secretariat, Geneva, 210 pp.
Bender, S., 2002. Development and use of natural hazard vulnerability assessment techniques in the Americas. Nat. Hazards Rev. 3 (4), 136–138.
Bewket, W., Conway, D., in press. A note on the temporal and spatial variability of rainfall in the drought-prone Amhara region of Ethiopia. Int. J. Climatol, doi:10.1002/joc.1481.
Blenkinsop, S., Fowler, H.J., 2007. Changes in drought characteristics for Europe projected by the PRUDENCE regional climate models. Int. J. Climatol. 27 (12), 1595–1610.
Bogardy, I., Matyasovszky, I., Bardossy, A., Duckstein, L., 1994. A hydroclimatological model of areal drought. J. Hydrol. 153, 245–264.
Bonaccorso, B., Cancelliere, A., Rossi, G., 2003. An analytical formulation of return period of drought severity. Stoch. Environ. Res. Risk Assess. 17 (3), 157–174.
Box, G.E.P., Jenkins, G.M., Reinsel, G.C., 1994. Time Series Analysis, 'Forecasting and Control'. Prentice Hall, Englewood Cliffs, NJ.

Bras, R.L., 1990. Hydrology: An Introduction to Hydrologic Science. Addison-Wesley, Reading, Mass.
Briggs, W.M., Wilks, D.S., 1996. Estimating monthly and seasonal distributions of temperature and precipitation using the new CPC long-range forecasts. J. Climate 9, 818–826.
Burke, E.J., Brown, S.J., 2010. Regional drought over the UK and changes in the future. J. Hydrol. 394 (2010), 471–485.
Burke, E.J., Brown, S.J., Christidis, N., 2006. Modeling the recent evolution of global drought and projections for the twenty-first century with the Hadley centre climate model. J. Hydrometeorol. 7, 1113–1125.
Cancelliere, A., Salas, J.D., 2004. Drought length properties for periodic–stochastic hydrologic data. Water Resour. Res. 40, W02503. doi:10.1029/2002WR001750.
Cancelliere, A., Salas, J.D., 2010. Drought probabilities and return period for annual streamflows series. J. Hydrol. 391 (2010), 77–89.
Cancelliere, A., Mauro, G.D., Bonaccorso, B., Rossi, G., 2007. Drought forecasting using the Standardized Precipitation Index. Water Resour. Manage. 21, 801–819.
Cane, M.A., Zebiak, S.E., 1985. A theory for El Nino and the Southern Oscillation. Science 228, 1085–1087.
Carbone, J.G., Dow, K., 2005. Water resource management and drought forecasts in South Carolina. J. Am. Water Resour. Assoc. 41 (1), 145–155.
Cebrian, A.C., Abaurrea, J., 2006. Drought analysis based on a marked cluster Poisson model. J. Hydrometeorol. 7, 713–723.
Chang, T.J., 1990. Effects of drought on streamflow characteristics. J. Irrig. Drain. Eng. ASCE 116 (3), 332–341.
Chang, T.J., Kavvas, M.L., Delleur, J.K., 1984. Daily precipitation modeling by discrete autoregressive moving average processes. Water Resour. Res. 20 (5), 565–580.
Chang, T.J., Zheng, H., Kleopa, X.A., Teog, C.B., 1996. Development of an expert system for daily drought monitoring. J. Comput. Civil Eng. 10 (1), 20–24.
Changnon, S.A., Vonnahme, D.R., 2003. Impact of spring 2000 drought forecasts on midwestern water management. J. Water Resour. Plann. Manage. 129 (1), 18–25.
Changnon, S.A., Pielke Jr., R.A., Changnon, D., Sylves, R.T., Pulwarty, R., 2000. Human factors explain the increased losses from weather and climate extremes. Bull. Am. Meteorol. Soc. 81 (3), 437–442.
Chiew, F.H.S., McMahon, T.A., 2002. Global ENSO-streamflow teleconnection, streamflow forecasting and interannual variability. Hydrol. Sci. J. 47, 505–522.
Chowdhary, H., Singh, V.P., 2010. Reducing uncertainty in estimates of frequency distribution parameters using composite likelihood approach and copula-based bivariate distributions. Water Resour. Res. 46, W11516. doi:10.1029/2009WR008490.
Chung, C.H., Salas, J.D., 2000. Return period and risk of droughts for dependent hydrologic processes. J. Hydrol. Eng. 5 (3), 259–268.
Clausen, B., Pearson, C.P., 1995. Regional frequency analysis of annual maximum stream flow drought. J. Hydrol. 173, 111–130.
Cook, B., Miller, R., Seager, R., 2008. Dust and sea surface temperature forcing of the 1930s ‘‘Dust Bowl’’ drought. Geophys. Res. Lett. 35 (8), L08,710.
Cook, B.I., Cook, E.R., Anchukaitis, K.J., Seager, R., Miller, R.L., in press. Forced and unforced variability of twentieth century North American droughts and pluvial. Climate Dyn., doi:10.1007/s00382-010-0897-9.

Cordery, I., 1999. Long range forecasting of low rainfall. Int. J. Climatol. 19, 463–470.
Dhanya, C.T., Nagesh Kumar, D., 2009. Data mining for evolution of association rules for droughts and floods in India using climate inputs. J. Geophys. Res. 114, D02102. doi:10.1029/2008JD010485.
Douglas, E.M., Vogel, R.M., Kroll, C.N., 2002. Impact of streamflow persistence on hydrologic design. J. Hydrol. Eng. 7 (3), 220–227.
Downer, R., Siddiqui, M., Yevjevich, V., 1967. Application of runs to hydrologic droughts. In: Proc., Int. Hydrology Symp. Paper 63, vol. 1. Colorado State Univ., Fort Collins, Colo., pp. 496–505.
Dracup, J.A., Lee, K.S., Paulson, E.G., 1980a. On the statistical characteristics of drought events. Water Resour. Res. 16 (2), 289–296.
Dracup, J.A., Lee, K.S., Paulson, E.G., 1980b. On the definition of droughts. Water Resour. Res. 16 (2), 297–302.
Dubrovsky, M., Svoboda, M.D., Trnka, M., Hayes, M.J., Wilhite, D.A., Zalud, Z., Hlavinka, P., 2009. Application of relative drought indices in assessing climatechange impacts on drought conditions in Czechia. Theor. Appl. Climatol. 96, 155–171.
Duckstein, L., 1983. Trade-offs between various mitigation measures. In: Yevjevich, V. et al. (Eds.), Coping with Droughts. Water Resources, Littleton, Colo.
Dupuis, D.J., 2010. Statistical modeling of the monthly Palmer Drought Severity Index. J. Hydrol. Eng. 15, 796–807.
Durdu, O.F., 2010. Application of linear stochastic models for drought forecasting in the Buyuk Menderes river basin, western Turkey. Stoch. Environ. Res. Risk Assess. 24, 1145–1162.
Eshel, G., Cane, M.A., Farrell, B.A., 2000. Forecasting Eastern Mediterranean droughts. Month. Weather Rev. 128, 3618–3630.
Farokhnia, A., Morid, S., Byun, H.R., 2010. Application of global SST and SLP data for drought forecasting on Tehran plain using data mining and ANFIS techniques. Theor. Appl. Climatol. doi:10.1007/s00704-010-0317-4.
Favre, A.-C., El Adlouni, S., Perreault, L., Thiemonge, N., Bobee, B., 2004. Multivariate hydrological frequency analysis using copulas. Water Resour. Res. 40, W01101. doi:10.1029/2003WR002456.
Ferguson, Ian M., Dracup, John A., Duffy, Philip B., Philip, Pegion, Siegfried, Schubert, 2010. Influence of SST Forcing on Stochastic Characteristics of Simulated Precipitation and Drought. J. Hydrometeorol. 11, 754–769.
Ferna´ndez, B., Salas, J.D., 1999a. Return period and risk of hydrologic events. I: mathematical formulation. J. Hydrol. Eng. 4 (4), 297–307.
Ferna´ndez, B., Salas, J.D., 1999b. Return period and risk of hydrologic events. II: applications. J. Hydrol. Eng. 4 (4), 308–316.
Fernandez, B., Vergara, A., 1998. Risk of scarcity of monthly precipitation and streamflows in semiarid regions. Hydrol. Sci. J. 43 (5), 759–773.
Fernandez, C., Vega, J.A., Fonturbel, T., Jimenez, E., 2009. Streamflow drought time series forecasting: a case study in a small watershed in North West Spain. Stoch. Environ. Res. Risk Assess. 23, 1063–1070. doi:10.1007/s00477-008-0277-8.
Figueira, J., Greco, S., Erhgott, M. (Eds.), 2005. Multiple Criteria Decision Analysis: State of the Art Surveys. Springer Science and Business Media, Boston, USA.
Frevert, D.K., Cowan, M.S., Lane, W.L., 1989. Use of stochastic hydrology in reservoir operation. J. Irrigat. Drainage Eng., ASCE 115 (3), 334–343.
Frick, D.M., Bode, D., Salas, J.D., 1990. Effect of drought on urban water supplies. I: drought analysis. J. Hydrol. Eng. 116, 733–753.

Gabriel, K.R., Neumann, J., 1962. A Markov chain model for daily rainfall occurrences at Tel Aviv. Quart. J. Roy. Meteorol. Soc. 88, 90–95.
Genest, C., Favre, A.C., 2007. Everything you always wanted to know about copula modeling but were afraid to ask. J. Hydrol. Eng. 12 (4), 347–368.
Ghosh, S., Mujumdar, P.P., 2007. Nonparametric methods for modeling GCM and scenario uncertainty in drought assessment. Water Resour. Res. 43, W07405. doi:10.1029/2006WR005351.
Goddard, L., Mason, S.J., Zebiak, S.E., Ropelewski, C.F., Basher, R., Cane, M.A., 2001. Current approaches to seasonal to interannual climate predictions. Int. J. Climatol. 21, 1111–1152.
Gonz´ alez, J., Vald´ es, J.B., 2003. Bivariate drought recurrence analysis using tree ring reconstructions. J. Hydrol. Eng. 8 (5), 247–258.
Gonzalez, J., Valdes, J.B., 2004. The mean frequency of recurrence of in-timemultidimensional events for drought analyses. Nat. Hazards. Earth Syst. Sci. 4, 17–28.
Govindaraju, R.S., Rao, A.R., 2000. Artificial Neural Networks in Hydrology. Kluwer Academic Publishers, Amsterdam.
Gray, B.M., 1976. Medium term fluctuations of rainfall in Southeastern England. Quart. J. Roy. Meteorol. Soc. 102, 627–638.
Gupta, V.K., Duckstein, L., 1975. A stochastic analysis of extreme droughts. Water Resour. Res. 11 (2), 221–228.
Guttman, N.B., Wallis, J.R., Hosking, J.R.M., 1992. Spatial comparability of the Palmer Drought Severity Index. Water Resour. Bull. 28, 1111–1119.
Guven, O., 1983. A simplified semiempirical approach to probabilities of extreme hydrologic droughts. Water Resour. Res. 19 (1), 441–453.
Haan, C.T., 2002. Statistical Methods in Hydrology. The Iowa State University Press, Ames, Iowa.
Han, P., Wang, P.X., Zhang, S.Y., Zhu, D.H., 2010. Drought forecasting based on the remote sensing data using. ARIMA Models 51 (11–12), 1398–1403.
Hastenrath, S., 1995. Recent advances in tropical climate prediction. J. Climate 8, 1519–1532.
Hayes, M.J., Wilhelmi, O.V., Knutson, C.L., 2004. Reducing drought risk: bridging theory and and practice. Nat. Hazards. Rev. 5 (2), 106–113.
Heim, R., 2002. A review of twentieth-century drought indices used in the United States. Bull. Am. Meteorol. Soc. 83, 1149–1165.
Herweijer, C., Seager, R., Cook, E., 2006. North American droughts of the mid to late nineteenth century: a history, simulation and implication for Mediaeval drought. Holocene 16 (2), 159.
Herweijer, C., Seager, R., Cook, E., Emile-Geay, J., 2007. North American droughts of the last millennium from a gridded network of tree-ring data. J. Climate 20 (7), 1353–1376.
Hirsch, R.M., 1981. Stochastic hydrologic model for drought management. J. Water Resour. Plann. Manage. 107 (2), 303–313.
Hisdal, H., Tallaksen, L.M., 2003. Estimation of regional meteorological and hydrological drought characteristics: a case study for Denmark. J. Hydrol. 281, 230–247.
Hisdal, H., Stahl, K., Tallaksen, L., Demuth, S., 2001. Have streamflow droughts in Europe become more severe or frequent? Int. J. Climatol. 21, 317–333.
Hoerling, M., Kumar, A., 2003. The perfect ocean for drought. Science 299 (5607),

691.
Hollinger, S.E., Isard, S.A., Welford, M.R., 1993. A new soil moisture drought index for predicting crop yields. In: Preprints, Eighth Conf. on Applied Climatology, Anaheim, CA. Amer. Meteor. Soc., pp. 187–190.
Huang, W.-C., Chou, C.-C., 2005. Drought early warning system in reservoir operation: theory and practice. Water Resour. Res 41, W11406. doi:10.1029/2004WR003830.
Huang, W.C., Yuan, L.C., 2004. A drought early warning system on real-time multireservoir operations. Water Resour. Res. 40, W06401. doi:10.1029/2003WR002910.
Hughes, B.L., Saunders, M.A., 2002. A drought climatology for Europe. Int. J. Climatol. 22, 1571–1592.
Ines, A.V.M., Hansen, J.W., Robertson, A.W., in press, Enhancing the utility of daily GCM rainfall for crop yield prediction. Int. J. Climatol., doi:10.1002/joc.2223.
IPCC, 2007. Climate change 2007: the physical science basis. In: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., Miller, H.L. (Eds.), Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, p. 996.
Jamieson, D.G., Fedra, K., 1996. The 'Water ware' decision support system for riverbasin planning. 1. Conceptual design. J. Hydrol. 117, 163–211.
Joe, H., 1997. Multivariate Models and Dependence Concepts. Chapman and Hall, Boca Raton, Fla.
Johansson, A., Barnston, A., Saha, S., van den Dool, H., 1998. On the level and origin of seasonal forecast skill in northern Europe. J. Atmos. Sci. 55, 103–127.
Johnson, W.K., Kohne, R.W., 1995. Susceptibility of reservoirs to drought using Palmer index. J. Water Resour. Plann. Manage. 119 (3), 367–387.
Kao, S.C., Govindaraju, R.S., 2010. A copula-based joint deficit index for droughts. J. Hydrol. 380, 121–134.
Karamouz, M., Torabi, S., Araghinejad, S., 2004. Analysis of hydrologic and agricultural droughts in central part of Iran. J. Hydrol. Eng. 9 (5), 402–414.
Kiem, A.S., Franks, S.W., 2004. Multi-decadal variability of drought risk, Eastern Australia. Hydrol. Process. 18, 2039–2050.
Kim, T., Valdes, J.B., 2003. Nonlinear model for drought forecasting based on a conjunction of wavelet transforms and neural networks. J. Hydrol. Eng., ASCE 8 (6), 319–328.
Kim, T., Valdes, J.B., Aparicio, J., 2002. Frequency and spatial characteristics of droughts in the Conchos River Basin, Mexico. Water Int. 27 (3), 420–430.
Kim, T., Vald´ es, J.B., Yoo, C., 2003a. Nonparametric approach for estimating return periods of droughts in arid regions. J. Hydrol. Eng. 8, 237–246.
Kothavala, Z., 1999. The duration and severity of drought over eastern Australia simulated by a coupled ocean-atmosphere GCM with a transient increase in CO_2. Environ. Model. Softw. 14, 243–252.
Kumar, V., Panu, U., 1997. Predictive assessment of severity of agricultural droughts based on agro-climatic factors. J. Am. Water Resour. Assoc. 33 (6), 1255–1264.
Kushnir, Y., Seager, R., Ting, M., Naik, N., Nakamura, J., 2010. Mechanisms of tropical Atlantic SST influence on North American hydroclimate variability. J. Clim. 23, 5610–5628.
Lana, X., Burgue~no, A., 1998. Spatial and temporal characterization of annual

extreme droughts in Catalunya (NE Spain). Int. J. Climatol. 18, 93–110.
Lana, X., Mart´inez, M.D., Burgue ~ no, A., Serra, C., Mart´in-vide, J., G´ omez, L., 2006. Distributions of long dry spells in the Iberian Peninsula, years 1951–1990. Int. J. Climatol. 26, 1999–2021.
Lansford, H., 1979. Tree-rings; predictors of drought? Weatherwise 32, 194–199.
Latif, M., Barnett, T.P., Cane, M.A., Fliigel, M., Graham, N.E., von Storch, H., Xu, J.-S., Zebiak, S.E., 1994. A review of ENSO prediction studies. Climate Dyn. 9, 167–179.
Leilah, A.A., Al-Khateeb, S.A., 2005. Statistical analysis of wheat yield under drought conditions. J. Arid Environ. 61, 483–496.
Liu, W.T., Kogan, F.N., 1996. Monitoring regional drought using the vegetation condition index. Int. J. Remote Sens. 17, 2761–2782.
Liu, W.T., Negron-Juarez, R.I., 2001. ENSO drought onset prediction in northeast Brazil using NDVI. Int. J. Remote Sens. 22, 3483–3501.
Llamas, J., Siddiqui, M., 1969. Runs of precipitation series. Hydrology Paper 33. Colorado State University, Fort Collins, Colorado.
Lloyd, E.H., 1970. Return period in the presence of persistence. J. Hydrol. 10 (3), 202–215.
Loaiciga, H.A., Leipnik, R.B., 1996. Stochastic renewal model of low-flow streamflow sequences. Stoch. Hydrol. Hydraul. 10 (1), 65–85.
Loaiciga, H.A., Marino, M.A., 1991. Recurrence interval of geophysical events. J. Water Resour. Plann. Manage., ASCE 117 (3), 367–382.
Lohani, V.K., Loganathan, G.V., 1997. An early warning system for drought management using the palmer drought index. J. Am. Water Resour. Assoc. 33 (6), 1375–1386.
Lohani, V.K., Loganathan, G.V., Mostaghimi, S., 1998. Long-term analysis and shortterm forecasting of dry spells by the Palmer Drought Severity Index. Nord. Hydrol. 29 (1), 21–40.
Loukas, A., Vasiliades, L., Tzabiras, J., 2007. Evaluation of climate change on drought impulses in Thessaly, Greece. Eur. Water J. 17, 28.
Loukas, A., Vasiliades, L., Tzabiras, J., 2008. Climate change effects on drought severity. Adv. Geosci., 17, 23–29, <http://www.adv-geosci.net/17/23/2008/>.
Luo, L., Wood, E.F., 2007. Monitoring and predicting the 2007 US drought. Geophys. Res. Lett. 34, L22702. doi:10.1029/2007GL031673.
Luo, L., Wood, E.F., 2008. Use of Bayesian mering techniques in a multimodel seasonal hydrologic ensemble prediction system for the Eastern United States. J. Hydrometeorol. 9, 866–884.
Maraun, D. et al., 2010. Precipitation downscaling under climate change: recent developments to bridge the gap between dynamical models and the end user. Rev. Geophys. 48, RG3003. doi:10.1029/2009RG000314.
Margulis, S.A., McLaughlinm, D., Entekhabi, D., Dunne, S., 2002. Land data assimilation and estimation of soil moisture using measurements from the Southern Great Plains 1997 field experiment. Water Resour. Res. 38, 1299. doi:10.1029/2001WR001114.
Mathier, L., Perreault, L., Bob´ ee, B., Ashkar, F., 1992. The use of geometric and gamma-related distributions for frequency analysis of water deficit. Stoch. Hydrol. Hydraul. 6, 239–254.
Maurer, E.P., Wood, A.W., Adam, J.C., Lettenmaier, D.P., Nijssen, B., 2002. A longterm hydrologicly-based data set of land surface fluxes and states for the conterminous United States. J. Climate 15, 3237–3251.

Mavromatis, T., 2007. Drought index evaluation for assessing future wheat production in Greece. Int. J. Climatol. 27, 911–924.
McKee, T.B., Doesken, N.J., Kleist, J., 1993. The relationship of drought frequency and duration to time scales. In: Paper Presented at 8th Conference on Applied Climatology, Am. Meteorol. Soc., Anaheim, Calif.
McVicar, T.R., Jupp, D.L.B., 1998. The current and potential operational uses of remote sensing to aid decisions on drought exceptional circumstances in australia: a review. Agric. Syst. 57, 399–468.
Merabtene, T., Kawamura, A., Jinno, K., Olsson, J., 2002. Risk assessment for optimal drought management of an integrated water resources system using a genetic algorithm. Hydrol. Process. 16, 2189–2208.
Millan, J., Yevjevich, V., 1971. Probabilities of observed droughts. Hydrology Paper No. 50. Colorado Slate University, Fort Collins, Colorado, USA.
Mishra, A.K., Coulibaly, P., 2009. Developments in hydrometric network design: a review. Rev. Geophys. 47, RG2001. doi:10.1029/2007RG000243.
Mishra, A.K., Desai, V.R., 2005a. Drought forecasting using stochastic models. J. Stoch. Environ. Res. Risk Assess. 19, 326–339.
Mishra, A.K., Desai, V.R., 2005b. Spatial and temporal drought analysis in the Kansabati River Basin, India. Int. J. River Basin Manage. 3 (1), 31–41.
Mishra, A.K., Desai, V.R., 2006. Drought forecasting using feed forward recursive neural network. Int. J. Ecol. Model. 198, 127–138.
Mishra, A.K., Singh, V.P., 2008. Development of drought SAF curves. In: Singh, V.P. (Ed.), Hydrology and Hydraulics. Water Resour. Publ., Highlands Ranch, Colo, pp. 811–831.
Mishra, A.K., Singh, V.P., 2009a. Decadal drought analysis using GCM outputs. In: International Conference on Water, Environment, Energy and Society, New Delhi, India.
Mishra, A.K., Singh, V.P., 2009b. Analysis of drought severity–area–frequency curves using a general circulation model and scenario uncertainty. J. Geophys. Res. 114, D06120. doi:10.1029/2008JD010986.
Mishra, A.K., Singh, V.P., 2010. A review of drought concepts. J. Hydrol. 391 (1–2), 202–216.
Mishra, A.K., Singh, V.P., in press. Seasonal streamflow extremes in Texas River basins: uncertainty, trends and teleconnections. J. Geophys. Res., doi:10.1029/ 2010JD014597.
Mishra, A.K., Desai, V.R., Singh, V.P., 2007. Drought forecasting using a hybrid stochastic and neural network model. J. Hydrol. Eng., ASCE 12 (6), 626–638.
Mishra, A.K., Singh, V.P., Desai, V.R., 2009. Drought characterization: a probabilistic approach. Stoch. Environ. Res. Risk Assess. 23 (1), 41–55.
Mishra, V., Cherkauer, K.A., Shukla, S., 2010. Assessment of drought due to historic climate variability and projected climate change in the Midwestern United States. J. Hydrometeorol. 11 (1), 46–68.
Mitchell, K.E., et al., 2004. The multi-institution North American Land Data Assimilation System (NLDAS): Utilizing multiple GCIP products and partners in a continental distributed hydrological modeling system. J. Geophys. Res. 109, D07S90. doi:10.1029/2003JD003823.
Mo, K., 2008. Model-based drought indices over the United States. J. Hydrometeorol. 562 (9(6)), 1212.
Modarres, R., 2007. Streamflow drought time series forecasting. Stoch. Environ. Res. Risk Assess. 15 (21), 223–233.

Mohan, S., Sahoo, P.K., 2007. Stochastic simulation of droughts. Part 1: point droughts. Hydrol. Process. 22 (6), 854–862.
Moradkhani, H., 2008. Hydrologic remote sensing and land surface data assimilation. Sensors 8, 2986–3004.
Moreira, E.E., Paulo, A.A., Pereira, L.S., Mexia, J.T., 2006. Analysis of SPI drought class transitions using loglinear models. J. Hydrol. 331, 349–359.