42. Na, M. K., Oh, W. K., Kim, Y. H., Cai, X. F., Kim, S. H., Kim, B. Y. and Ahn, J. S., Inhibition of protein tyrosine phosphatase 1B by diterpenoids isolated from *Acanthopanax koreanum*. *Bioorg. Med. Chem. Lett*., 2006, **16**, 3061–3064.
43. Hoang, D. M. *et al*., Protein tyrosine phosphatase 1B inhibitors isolated from *Morus bombycis*. *Bioorg. Med. Chem. Lett*., 2009, **19**, 6759–6761.
44. Seo, C., Sohn, J. H., Oh, H., Kim, B. Y. and Ahn, J. S., Isolation of the protein tyrosine phosphatase 1B inhibitory metabolite from the marine-derived fungus *Cosmospora* sp. SF-5060. *Bioorg. Med. Chem. Lett*., 2009, **19**, 6095–6097.
45. Popov, D., Novel protein tyrosine phosphatase 1B inhibitors: interaction requirements for improved intracellular efficacy in type 2 diabetes mellitus and obesity control. *Biochem. Biophys. Res. Commun*., 2011, **410**, 377–381.
46. Kurundkara, S. B., Sachanb, N., Kodama, K. M., Kulkarni, V. M., Bodhankarc, S. L. and Gholea, V. S., Antihyperglycemic activity of VMNS2E, a novel biphenyl PTP1B inhibitor and its effect on insulin resistance, diabetes and dyslipidemia. *Diabetes Vasc. Dis. Res*., 2011, **8**, 91–93.
47. Muthusamy, V. S., Saravanababu, C., Ramanathan, M., Bharathi Raja, R., Sudhagar, S., Anand, S. and Lakshmi, B. S., Inhibition of protein tyrosine phosphatase 1B and regulation of insulin signalling markers by caffeoyl derivatives of chicory (*Cichorium intybus*) salad leaves. *Br. J. Nutr*., 2010, **104**, 813–823.
48. Liu, S. *et al*., Targeting inactive enzyme conformation: aryl diketoacid derivatives as a new class of PTP1B inhibitors. *J. Am. Chem. Soc*., 2008, **130**, 17075.
49. Bialy, L. and Waldmann, H., Inhibitors of protein tyrosine phosphatases: next-generation drugs? *Angew Chem., Int. Ed. Engl*., 2005, **44**, 3814–3839.
50. Curtis, J., Greenberg, M., Kester, J., Phillips, S. and Krieger, G., Nanotechnology and nanotoxicology: a primer for clinicians. *Toxicol. Rev*., 2006, **25**, 245–260.
51. Espín, J. C., García-Conesa, M. T. and Tomás-Barberán, F. A., Nutraceuticals: facts and fiction. *Phytochemistry*, 2007, **68**, 2986–3008.
52. Rochfort, S. and Panozzo, J., Phytochemicals for health, the role of pulses. *J. Agric. Food Chem*., 2007, **55**, 7981–7994.
53. Setchell, K. D. R. *et al*., Bioavailability of pure isoflavones in healthy humans and analysis of commercial soy isoflavone supplements. *J. Nutr*., 2001, **131**, 1362S–1275S.
54. Magee, P. J. and Rowland, I. R., Phyto-oestrogens, their mechanism of action: current evidence for a role in breast and prostate cancer. *Br. J. Nutr*., 2004, **91**, 513–520.
55. Limer, J. L. and Speirs, V., Phyto-oestrogens and breast cancer chemoprevention. *Breast Cancer Res*., 2004, **6**, 119–127.
56. Bandele, O. J. and Osheroff, N., Epigallocatechin Gal-late, a major constituent of green tea, poisons human type II topoisomerases. *Chem. Res. Toxicol*., 2008, **21**, 936–943.
57. Shankar, S., Ganapathy, S. and Srivastava, R. K., Green tea polyphenols: biology and therapeutic implications in cancer. *Front. Biosci*., 2007, **12**, 4881–4899.
58. Dannemann, K. *et al*., Use of complementary and alternative medicine in children with type 1 diabetes mellitus – prevalence, patterns of use and costs. *Pediatr Diabetes*, 2008, **9**, 228–235.
59. Suppapitiporn, S. and Kanpaksi, N., The effect of cinnamon cassia powder in type 2 diabetes mellitus. *J. Med. Assoc. Thailand*, 2006, **89**, 200–205.

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Model for determining geometry of wetted soil zone under subsurface drip irrigation

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A model was developed using dimensional analysis approach for determining geometry of wetted soil zone under point sources of water application with subsurface drip irrigation (SDI). The predicted values of wetted depth and width were compared with those obtained through field experiments conducted in black vertisols at the Central Institute of Agricultural Engineering, Bhopal, India. Experimentation included determination of maximum depths and widths of wetted soil zone after 0.5, 1, 2, 3 and 5 h of water application through SDI laterals placed at 0.05, 0.10, 0.15, 0.20 and 0.25 m depths below the soil surface. The effect of discharge, depths of placement of laterals and duration of water application on wetted width and depth were observed. Statistical analysis revealed no significant difference between predicted and observed values of wetted width and depth. Predictability of model expressed in terms of model efficiency was found to be 88.7% and 93.3% for wetted width and depth respectively. Therefore, the developed model could be used to simulate wetted depth and width under SDI with point source of water application.

Keywords: Dimensional analysis, model efficiency, soil water content, subsurface drip irrigation.

TRADITIONALLY surface method of irrigation being used in major areas in India has low field-level application efficiency of only 35–40% because of huge conveyance and distribution losses[1,2]. Whereas about 2 million hectare (m ha) land under horticulture and vegetable crops is being irrigated through both sprinkler and drip irrigation. It improves[2] irrigation control with smaller frequent application, supplies nutrients to the crop as needed; results in less weed growth and improved crop yields by 50%, water saving by 315% and water-use efficiency by 119%. Drip irrigation may achieve field-level application efficiency of 80–90%, as surface run-off and deep percolation losses are minimized[3–5]. Area under drip irrigation is likely to increase, to realize enhanced water-use efficiency and crop yield as well as sustainable management of irrigation water[6,7]. It has vast potential of 27 m ha in India[8,9]. It is suitable for areas that are presently under

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cultivation and can also be used efficiently in undulating terrain, rolling topography, hilly areas, barren land and areas which have shallow soils[10]. Also, drip irrigation can be made more applicable for irrigating a wide range of agronomic, horticultural and fruit crops by installing the laterals below the soil surface, called subsurface drip irrigation (SDI)[11].

Studies worldwide have revealed the advantages of SDI of many crops over the surface drip as well as other irrigation methods – reduced evaporation loss and precise placement and management of water, nutrient and pesticides leading to more efficient water use, greater water application uniformity, enhanced plant growth, crop yield and quality[12–27]. Few studies conducted in India also indicate great potential of SDI for application in horticultural and vegetable crops for enhanced crop yield and water saving[28–38]. One of the important aspects of planning and management of the SDI system is soil moisture movement pattern under it. It is important in deciding depth of lateral placement below soil surface, emitter spacing and system pressure for delivering the required amount of water to the plant.

Wetting pattern can be obtained by either direct measurement of soil wetting in field, which is site-specific, or by simulation using some models. Since water movement in soil under drip irrigation is predominantly unsaturated flow, in most of models the Richard's equation (eq. (1) below) governing water flow under unsaturated flow conditions is widely used to simulate soil water matric potential or water content distribution in wetted soil. Development of models for design tools of drip irrigation was based on analytical and numerical solution of the unsaturated flow equations to simulate the soil water movement under drip irrigation.

$$\frac{\partial}{\partial x}\left(K_x \frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_y \frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_z \frac{\partial h}{\partial z}\right)=\frac{\partial \theta}{\partial t} \quad (1)$$

where h is the total potential; K_x, K_y and K_z are the hydraulic conductivities of soil in X, Y and Z directions respectively; x, y and z are the dimensions of soil volume; θ is the volumetric water content and t is the time.

In many situations, the use of numerical or analytical flow models for design purpose displays high spatial variability, is considered cumbersome and impractical[39–41]. These require many soil physical parameters which are generally not readily available for many soils. These solutions also require many simplifying assumptions that limit their applicability in practical field conditions, and large differences were observed between simulated and observed values. In practical situations prediction of wetted boundary and shape of soil volume is sufficient to deal with the situation. Therefore, simplified simulation models for soil wetting pattern were developed which predict wetting front position.

A simplified semi-empirical approach was developed for determining the geometry of wetted soil zone under line sources of water application placed on the surface[42]. The maximum wetted depth and width of soil with SDI depend on discharge of emitter, duration of water application and hydraulic conductivity of soil. Thus the complexities encountered in numerical and analytical methods for designing are reduced.

The geometry of wetted soil volume, width and depth under SDI system with line source of water application at the end of an irrigation event depends on discharge per unit length of the laterals, total amount of water in the soil per unit length of the lateral, depth of lateral placement below soil surface and hydraulic conductivity of the soil[28,29,43]. As the hydraulic conductivity of the soil is dependent on soil water content, it could be replaced with a function of water content of soil. Therefore, simplified model using dimensional analysis method was developed for finding out the wetted depth and width under different placement depths of SDI for point source water application.

The model for simulating wetted depths and widths with point source of water application was developed assuming that hydraulic conductivity can be replaced with a function of water content of soil. Therefore, wetted depths and widths depend on depth of placement of laterals, discharge of emitter, duration of water application and change in water content of soil over time. Therefore, the functional relationship among parameters may be written as

$$f(W', D', Z', Q', t', \theta') = 0, \quad (2)$$

where W' is the maximum width of the wetted soil volume (L), D' the maximum wetted depth of the soil (L), Z' the depth of placement of lateral (L), Q' the discharge of emitter (L^3/T), t' the duration of water application (T) and θ' is the change in water content of soil (L^3/L^3).

Using dimensional analysis method, four dimensional-independent π-terms were developed which are represented as follows

$$f(\pi'_1, \pi'_2, \pi'_3, \pi'_4) = 0, \quad (3)$$

where

$$\pi'_1 = (W'/Z'), \quad (4)$$

$$\pi'_2 = \theta', \quad (5)$$

$$\pi'_3 = (D'/Z'), \quad (6)$$

$$\pi'_4 = (Q't'/Z'^3). \quad (7)$$

Dimensionless terms were obtained by a combination of the above dimensionless π-terms as below:

1. Multiplication of second and fourth π-terms resulted in dimensionless time, t'^*:

$$t'^* = t'Q'(\theta'/Z'^3). \tag{8}$$

2. Cubic root of multiplication of second and cube of first π-term resulted in dimensionless wetted width, W'^*:

$$W'^* = W'(\theta'/Z'^3)^{1/3}. \tag{9}$$

3. Cubic root of multiplication of second and cube of third π-term resulted in dimensionless wetted depth, D'^*:

$$D'^* = D'(\theta'/Z'^3)^{1/3}. \tag{10}$$

Both dimensionless wetted depth and width can be represented in terms of dimensionless time. It may be implicit that the following relationships exist between the above dimensionless parameters[28,29,42]:

$$W'^* = A_1' t'^{*n_1'}, \tag{11}$$

$$D'^* = A_2' t'^{*n_2'}, \tag{12}$$

where A_1' and A_2' are constants and n_1' and n_2' are exponents of eqs (11) and (12) respectively.

The values of A_1' and n_1' were obtained by a graphical relationship between W'^* and t'^*; and A_2' and n_2' were obtained by a graphical relationship between D'^* and t'^*. Now putting values of W'^* and t'^* in eq. (11), the following relationship for wetted width can be obtained:

$$W' = A_1' \left(t'Q'\right)^{n_1'} (\theta'/Z'^3)^{(n_1' - \frac{1}{3})}. \tag{13}$$

Similarly, wetted depth can be obtained by putting values of D'^* and t'^* in eq. (12) as below

$$D' = A_2' \left(t'Q'\right)^{n_2'} (\theta'/Z'^3)^{(n_2' - \frac{1}{3})}. \tag{14}$$

SDI laterals placed at 5, 10, 15, 20 and 25 cm depths below the soil surface, and emitter discharge rates of 1.3, 2, 2.3 and 3 litre per hour (lph) discharge rates at various spacings on laterals were operated for 0.5, 1, 2, 3 and 5 h duration. At the end of each irrigation event, the depths and widths of wetted zone soil were recorded. The wetted zones soil of SDI with emitter discharge 1.3 lph and emitter spacing on lateral 0.20 m behaved as point source up to 1 h duration of water application. The wetted width was 18.5–19.5 cm for 5–25 cm placement depth of the lateral with wetted depth as 18.5–17.0 cm.

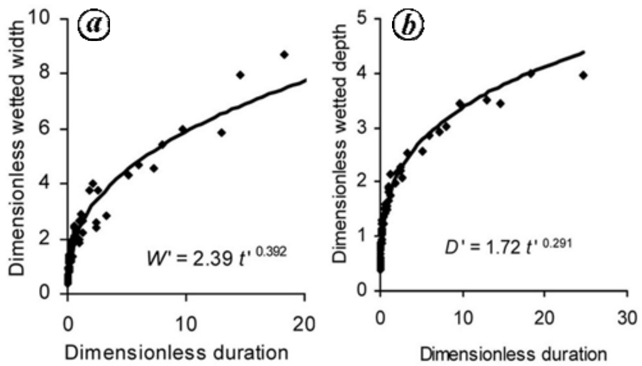

Figure 1. Relationship between dimensionless wetted soil width (***a***) and wetted soil depth (***b***), and dimensionless duration of water application with point source.

The SDI with emitter discharge 2 lph and emitter spacing on lateral 0.30 m worked as point source up to 1 h duration for all placement depths of lateral. Maximum wetted width of soil was 22.5–20.9 cm and wetted depth 20.5–23.5 cm for lateral placement depths of 5 to 25 cm. While that with emitter spacing on lateral 40 cm worked as point source up to 2 h of water application for all placement depths of lateral with maximum wetted depth and width of 23.5–31.5 cm and 39.5–29.5 cm respectively, for 5–25 cm lateral placement depths. However, SDI with emitter discharge rate 2 lph and emitter spacing on lateral 50 cm worked as point source up to 3 h of operation for all placement depths of lateral with wetted depth and width of 27.5–40.0 cm and 50.0–41.5 cm respectively, under 5–25 cm lateral placement depths.

The SDI with 3 lph emitter discharge rate spaced at 75 and 90 cm on laterals worked as point source up to 5 h of operation of SDI system for 5–25 cm placement depths of lateral. The maximum wetted width and depth of soil was found as 74 and 50 cm with 5 cm and 25 cm placement depth of lateral in soil respectively.

The developed models were validated under field conditions for a wide range of placement depths of SDI lateral and emitter discharge. The experiment was designed with five treatments as depths of lateral placement, i.e. 0.05, 0.10, 0.15, 0.20 and 0.25 m below the soil surface and on the soil surface for emitter discharge rate of 1.3, 2, 2.3 and 3 lph. Observations on depths and widths of wetted soil with SDI after 0.5, 1, 2, 3, and 5 h of water application were recorded[43]. The values of W' and D' were estimated using data of the experiment as shown in Figure 1 *a* and *b* respectively[28,29,42].

The following relations for D' and W' of wetted zone soil with point source water application were yielded from the figure.

$$W' = 2.39\left(t'Q'\right)^{0.392} (\theta'/Z'^3)^{0.059}, \tag{15}$$

and

$$D' = 1.72\left(t'Q'\right)^{0.291}(\theta'/Z'^3)^{-0.042}. \quad (16)$$

Boundary conditions for above equations are: duration of irrigation event, $t = 0.5$–5 h; lateral placement depth, $Z' = 0.05$–0.25 m; emitter discharge rate, $Q' = 1.3$–3.0 lph.

The values of wetted widths and wetted depths of soil were simulated using eqs (15) and (16) for different discharge rates, duration of water application and depths of placement of laterals.

The performance and applicability of developed models were evaluated using statistical parameters. Performance of the model was tested by comparing model values against observed values in field and laboratory to ensure model validity under field conditions. Therefore, null-hypotheses of equal variances and equal means at 0.05 level of significance were tested using *t*-test and *Z*-test respectively. These tests were performed separately for each lateral of different discharge rate having normal and independent observations for comparing model values against observed values of wetted soil depth and width for a given duration of water application. Null-hypotheses of equal variances and mean respectively were accepted to conclude that model values followed distribution not different than the observed values, if the values of *t* and *Z*-statistics were found less than their table values at 0.05 level of significance.

Performance evaluation of the model was also based on comparison of statistical parameters of model data with those of observed data. The parameters used were mean error (ME), root mean square error (RMSE) and model efficiency (EF), which were calculated using the following relationships[44].

$$\mathrm{RMSE} = \left[\frac{1}{N}\sum_{i=1}^{N}(C_{\mathrm{m}i} - C_{\mathrm{o}i})^2\right]^{1/2}, \quad (17)$$

$$\mathrm{ME} = \frac{1}{N}\sum_{i=1}^{N}(C_{\mathrm{m}i} - C_{\mathrm{o}i}), \quad (18)$$

$$\mathrm{EF} = 1 - \frac{\sum_{i=1}^{N}(C_{\mathrm{m}i} - C_{\mathrm{o}i})^2}{\sum_{i=1}^{N}(C_{\mathrm{o}i} - C_{\mathrm{o}})^2}, \quad (19)$$

where N is the total number of data, $C_{\mathrm{m}i}$ the *i*th model data, $C_{\mathrm{o}i}$ the *i*th observed data and C_{o} is the mean of observed data.

Magnitudes of RMSE values are indicative of performance of the model, but without showing degree of over or underestimation of model values. Statistical parameter ME was used for quantification of accuracy of model data in comparison to observed wetted soil depth and width. The positive value of ME is indicative of overestimation and negative value indicates underestimation. The absolute value of ME is an indicator of the performance of the model. RMSE, ME and EF values were compared separately for wetted width and depth of the soil. Lower the value of RMSE and absolute value of ME, and greater the value of EF, better is the performance of the model[44,45].

Comparison between transformed modelled and observed values of depth and width of wetted zone soil under different placement depths and discharge rates of laterals for different durations of operation with point source of water application is made (Figure 2). The logarithmic transformation, i.e. natural logarithm of values of observed and modelled wetted soil width and depth (cm) has been

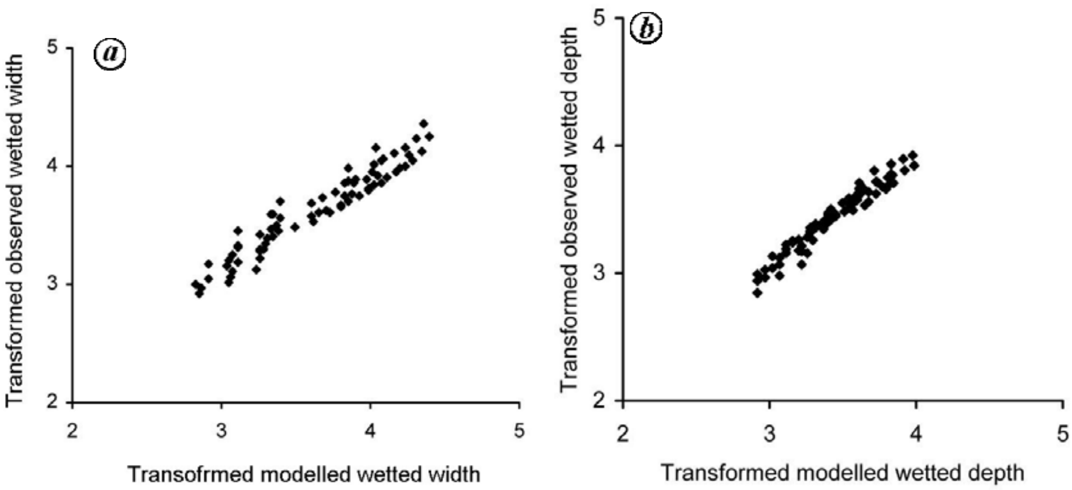

Figure 2. Transformed observed and modelled wetted width (***a***) and wetted depth (***b***) using developed model under subsurface drip irrigation with point source water application.

Table 1. Performance parameters of model for width and depth of wetted zone soil under subsurface drip irrigation with point source water application

Performance parameters	Values of parameters for wetted zone soil with Wetted width	Wetted depth
Root mean square error (m)	0.062	0.024
Mean error (m)	–0.014	–0.003
Model efficiency (%)	88.7	93.3

used. The figure indicates the match between observed and modelled wetted width and depth of the soil.

The *t*- and *Z*-tests for null-hypothesis of equal variances and means respectively, at 0.05 level of significance and 48 degree of freedom were used to test modelled data against observed data for each lateral. The calculated values of *t*-statistics varied from –0.037 to 0.267, while that of *Z*-statistics varied from –0.038 to 0.271. Critical (table) values of *t* and *Z* were 2.01 and 1.96 respectively, at 0.05 level of significance. The calculated values of *t* and *Z*-statistics were found to be less than their critical values for all SDI. Therefore, null-hypotheses were accepted. Hence, it may be concluded that modelled values of depths and widths of wetted zone soil were not significantly different than those observed under SDI systems.

RMSE, ME and EF values for the developed model are presented in Table 1. Smaller values of RMSE and ME are indicators of good performance of the model. The model was found underestimating and overestimating values of wetted soil depth and width as indicated by negative and positive values of ME respectively. Slight variation in modelled values compared to observed values can be attributed to empirical nature of developed model. Performance of the model was good with model efficiency of 88–93%, for width and depth of wetted zone soil respectively.

The present results indicate that the developed model describes wetted depths and widths of soil under SDI. Therefore, the model could be used to describe wetted depths and widths of soil under SDI system with point source of water application.

In conclusion, dimensional analysis method was used for development of model to simulate soil wetted depth and width under SDI with point source water application. The simulated wetted soil width and depth were compared with test model applicability in field conditions. The results of *Z*-test and *t*-test indicated that the distribution of model-simulated values were not different from the observed ones. The developed models have good performance with high model efficiency varying from 88% to 93%, and lower values of RMSE and ME. The developed model can be used to predict wetted depth and width with point source water application through SDI system.

1. INCID, Drip irrigation in India, New Delhi, Indian National Committee on Irrigation and Drainage, 1994.
2. Rosegrant, W. M., Water resources in the twenty-first century: challenges and implications for action. Food and agriculture, and the environment discussion paper 20, International Food Policy Research Institute, Washington DC, USA, March 1997.
3. Heermann, D. F., Wallender, W. W. and Bos, M. G., Irrigation efficiency and uniformity. In *Management of Farm Irrigation System* (eds Hoffman, G. S., Howell, T. A. and Soloman, K. H.), American Society of Agricultural Engineers, St Joseph, MI, USA, 1990, pp. 125–149.
4. Sivanappan, R. K., Irrigation water management for sugarcane, Vasantdada Sugar Institute, 1998, pp. 100–125.
5. Postel, S., Redesigning irrigated agriculture. In *State of the World* (ed. Stark, L.), W. Norton and Co, New York, 2000, pp. 39–58.
6. Singh, D. K., Chandola, V. K. and Singh, R. M., *Sustainable Management of Irrigation Water. An Approach to Address Impact of Climate Change in Agriculture*, Flair Book Publication, New Delhi, 2009, p. 206.
7. Singh, D. K., Singh, R. M. and Chandola, V. K., Sustainable water management in agriculture: issues and strategies to address. In Proceedings of National Seminar on Sustainable Management of Water Resources, Institute of Agricultural Sciences, Banaras Hindu University, Varanasi, 14–15 January 2011, pp. 59–74.
8. Narayanamoorthy, A., Drip irrigation in India: can it solve water scarcity? *Water Policy*, 2004, **6**, 117–130.
9. Report of Task Force on Microirrigation, Ministry of Agriculture, Government of India, 2004.
10. Sivanappan, R. K., Prospects of micro irrigation in India. *Irrig. Drain. Syst.*, 1994, **8**, 49–58.
11. ASAE Standards, S 526.1, Soil and water terminology. American Society of Agricultural Engineers Standards, St Joseph, MI, USA, 1999.
12. Hernandez, J. J. M., Bar-Yosef, B. and Kafkali, U., Effect of surface and subsurface drip fertigation on sweet corn rooting, uptake, dry matter production and yield. *Irrig. Sci*., 1991, **12**, 153–159.
13. Evett, S. R., Howell, T. A. and Schneider, A. D., Energy and water balances for surface and subsurface drip irrigated corn. In Proceedings of the Fifth International Micro Irrigation Congress, Orlando, FL, USA, 2–6 April 1995, pp. 135–140.
14. Lamm, F. R., Manges, H. L., Stone, L. R., Khan, A. H. and Rogers, D. H., Water requirement of subsurface drip irrigated corn in northwest Kansas. *Trans. ASAE*, 1995, **38**, 441–448.
15. Burt, C. M. *et al.*, Irrigation performance measures: efficiency and uniformity. *J. Irrig. Drain. Eng.*, 1997, **123**, 423–442.
16. Camp, C. R., Bauer, P. J. and Hunt, P. G., Subsurface drip irrigation lateral spacing and management for cotton in the southern coastal plain. *Trans. ASAE*, 1997, **40**, 993–999.
17. Camp, C. R., Subsurface drip irrigation: a review. *Trans. ASAE*, 1998, **41**, 1353–1367.
18. Ayars, J. E., Phene, C. J., Hutmacher, R. B., Davis, K. R., Schoneman, R. A., Vail, S. S. and Mead, R. M., Subsurface drip irrigation of row crops: a review of 15 years of research at the water management research laboratory. *Agric. Water Manage.*, 1999, **42**, 1–27.
19. Phene, C. J., Subsurface drip irrigation offers management advantages, 2000; http://www.Geoflow.com/agriculture/phene.htm
20. Charlesworth, P. B. and Muirhead, W. A., Crop establishment using subsurface drip irrigation: a comparison of point and area source. *Irrig. Sci.*, 2003, **22**, 171–176.
21. Lamm, F. R. and Trooien, T. P., Subsurface drip irrigation for corn production: a review of 10 years of research in Kansas. *Irrig. Sci*., 2003, **22**, 195–200.
22. Toderich, K., Abbdusarnatov, M. and Tsukatani, T., Water research assessment, irrigation and agricultural development in Tajikistan. Discussion Paper No. 585, Tyoto Institute of Economics Research, Kyota University, 2004.

23. Hanson, B. and May, D., Effect of subsurface drip irrigation on processing tomato yield, water table depth, soil salinity, and profitability. *Agric. Water Manage*., 2004, **68**, 1–17.
24. Grabow, G. L., Huffman, R. L., Evans, R. O., Jordan, D. L. and Nuti, R. C., Water distribution from a subsurface drip irrigation system and dripline spacing effect on cotton yield and water use efficiency in a coastal plain soil. *Trans. Am. Soc. Agric. Biol. Eng*., 2006, **49**, 1823–1835.
25. Vories, E. D., Tacker, P. L., Lancaster, S. W. and Glover, R. E., Subsurface drip irrigation of corn in the United States Mid-South. *Agric. Water Manage*., 2009, **96**, 912–916.
26. Arbat, G., Lamm, F. R. and Abou Kheira, A. A., Subsurface drip irrigation emitter spacing effects on soil water redistribution, corn yield and water productivity. *Appl. Eng. Agric.*, 2010, **26**, 391–399.
27. Douh, B. and Boujelben, A., Effects of surface and subsurface drip irrigation on agronomic parameters of maize (*Zea mays* L.) under Tunisian climatic condition. *J. Nat. Prod. Plant Resour*., 2011, **1**, 8–14.
28. Singh, D. K., Performance evaluation of subsurface drip irrigation systems. Ph D thesis, Indian Agricultural Research Institute, New Delhi, 2004.
29. Singh, D. K., Rajput, T. B. S., Singh, D. K., Sikarwar, H. S., Sahoo, R. N. and Ahmad, T., Simulation of soil-wetting pattern under subsurface drip irrigation system with line source of water application. *Agric. Water Manage*., 2006, **83**, 130–134.
30. Singh, D. K., Rajput, T. B. S., Singh, D. K., Sikarwar, H. S., Sahoo, R. N. and Ahmad, T., Performance of subsurface drip irrigation systems with line source of water application in okra field. *J. Agric. Eng.*, 2006, **43**, 23–26.
31. Luthra, S. K. and Pandey, R. S., Enhancement of water productivity in subsurface micro irrigation through automation in irrigation. In 41st Annual Convention and Symposium of Indian Society of Agricultural Engineers, 29–31 January 2007.
32. Patel, N. and Rajput, T. B. S., Effect of subsurface drip irrigation on onion production. In 41st Annual Convention and Symposium of Indian Society of Agricultural Engineers, 29–31 January 2007.
33. Singh, D. K. and Rajput, T. B. S., Response of lateral placement depths of subsurface drip irrigation on okra (*Abelmoschus esculentus*). *Int. J. Plant Prod*., 2007, **1**, 73–84.
34. Singh, D. K., Rao, K. V. R., Singh, R. M. and Reddy, K. S., Subsurface drip irrigation in vertisols. Technical Bulletin No. CIAE/2008/135, Central Institute of Agricultural Engineering (CIAE), Bhopal, 2008, p. 18.
35. Patel, N. and Rajput, T. B. S., Dynamics and modeling of soil water under subsurface drip irrigated onion. *Agric. Water Manage.*, 2008, **95**, 1335–1349.
36. Patel, N. and Rajput, T. B.S., Effect of subsurface drip irrigation on onion yield. *Irrig. Sci.*, 2009, **27**, 97–108.
37. Singh, D. K., Singh, R. M. and Rao, K. V. R., Scope of subsurface drip irrigation in the state of Chhattisgarh. *Agric. Eng. Today*, 2010, **34**, 24–30.
38. Singh, D. K., Singh, R. M., Rao, K. V. R., Kishore, R. and Singh, K., Effect of subsurface drip, surface drip, micro sprinkler and furrow irrigation on tomato in vertisols. In Proceeding of National Seminar on Sustainable Management of Water Resources, Institute of Agricultural Sciences, BHU, Varanasi, 14–15 January 2011, pp. 95–104.
39. Warrick, A. W. and Nielson, D. R., Spatial variability of soil physical properties in the field. In *Applications in Soil Physics* (ed. Hillel, D.), Academic Press, New York, 1980, p. 319.
40. Lafolie, F., Bruckler, L., de Cockborne, A. M. and Laboucarie, C., Modelling the water transport and nitrogen dynamics in irrigated salad crops. *Irrig. Sci*., 1997, **17**, 95–104.
41. Battam, M. A., Sutton, B. G. and Boughton, D. G., Soil pit as a simple design aid for subsurface drip irrigation systems. *Irrig. Sci*., 2003, **22**, 135–141.
42. Schwartzman, M. and Zur, B., Emitter spacing and geometry of wetted soil volume. *J. Irrig. Drain. Eng. ASCE*, 1986, **112**, 242–253.
43. Singh, D. K., Singh, R. M. and Rao, K. V. R., Optimization of design parameters for subsurface drip irrigation system in vertisols. Final Report of Research Project, CIAE, Bhopal, 2008.
44. Willmut, C. J., Some comments on the evaluation of model performance. *Bull. Am. Meteorol. Soc*., 1982, **63**, 1309–1313.
45. Jacovides, C. P. and Kontoyiannis, H., Statistical procedures for the evaluation of evapotranspiration computing models. *Agric. Water Manage*, 1995, **27**, 365–371.

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Chemical analysis of ancient mortar from excavation sites of Kondapur, Andhra Pradesh, India to understand the technology and ingredients

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In the present study, lime mortar sample from a recently excavated historical site has been analysed by X-ray diffraction (XRD), scanning electron microscope coupled with energy dispersive X-ray system (SEM-EDX), thermogravimetric analysis/differential thermal analysis (TGA/DTA), particle-induced X-ray emission (PIXE) and chemical analysis. From chemical analysis the binder aggregate (B/Ag) ratio of 1 : 3 has been reported. Calcite is the most abundant mineral present in the mortar identified by XRD. Microstructure along with texture and elemental composition of the final product was studied with SEM-EDX, which is in agreement with chemical analysis. The weight loss as a function of temperature was studied from thermal analysis. Trace elements were studied by vacuum PIXE.

Keywords: Ancient monuments, chemical analysis, excavation sites, lime mortar.

APPLICATION of lime mortar in ancient heritage buildings is an old practice. Elemental composition of archaeologi-

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