An Integrated Approach Involving EMO and HYDRUS-2D Software for SWRT-based Precision Irrigation

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***Abstract*—Retaining water at the root level of crops has been a major focus in precision irrigation system from technological, societal, and environmental points of view. Subsurface water retention technology (SWRT) through impermeable membranes placed at certain depths under has shown 1.4 to 3.4-fold increase in production in crops. However, the sizing, placement and surface water scheduling are important parameters for achieving an optimal yield. In this paper, for the first time, we consider a water flow simulation model through soil (HYDRUS-2D) is integrated with an evolutionary multi-objective optimization (EMO) algorithm to find optimal membrane configurations and surface water supply under multiple conflicting objectives. The initial results presented in this paper clearly demonstrate the merit of such a collaboration and supports further studies. Not only the integrated approach finds optimal membrane configurations and water supply, but also reveals a number of useful insights and knowledge about optimal precision irrigation, a matter which has long term contributions to water conservation, groundwater preservation, and many natural resources directly affecting modern society.**

I. Introduction

Water is vital for irrigation of crops but water is also scarce and today's food and cellulosic biomass producers must make a judicial use of water for irrigation. On the other hand, abundant or adequate water is available in certain places and at certain times through rainfall. In such lands, prolonged storage or rainwater in plant root zones would require less supply of additional irrigation water. As the water availability and supply is different in different places, different crops require different amounts of water and nutrients during their growth. Thus, irrigation water supply for a healthy crop growth depends on quite many factors, such as soil type, moisture content in the soil, climatic conditions, crops to be grown, etc. Since water is precious and additional irrigation water supply is costly, farmers can be supported with sophisticated computational means of determining dynamic but *optimal* requirement of irrigation water.

National and international projections identify 65% more food and biomass production will be required to support global human populations approaching 9.6 bilion by requiring 50% more irrigation water by 2050 [1]. Additionally, this greater production must be accomplished using water more efficiently in a manner that avoids subjecting plants to frequent daily and prolonged water stress. It is believed that retaining more water in plant root zones, for longer periods of time, achievable with the new subsurface water retention technology SWRT [2], [3], [4], [5] dramatically reduces and eliminates a plethora of soil conditions that can cause plant drought. Smucker et al. [2] suggested a membrane based water retention technology in which bowl-shaped troughs of impermeable membranes are placed at certain depth below the soil surface in a systematic staggered manner. The supplied irrigation water permeates along with nutrients stored within the membranes, thereby allowing the plants to have a constant supply of water stored within their root system. This SWRT technology is shown to increase the productivity to 1.4 to 3.4-fold [5]. It is clear that the amount of retained water at the root of the plants depends on the size and the aspect ratio of the membranes. Any excess water can then move downwards into the water table.

It is amply clear that the SWRT technology along with a judicious surface or subsurface water irrigation system is an effective means of efficient irrigation of twenty-first century. However, the technology requires determination of an optimal supply of irrigation water and also optimal sizing and placement of subsurface membranes. This requires coupling of a computational model of the water permeation through soil with an optimization algorithm. Due to multidisciplinary consideration involving cost of supplying irrigation water and dependency of water on plant growth, the optimization problem has multiple objectives, thereby requiring a multi-objective optimization method to solve such practical problems. In this paper, we make an effort in this direction and integrate a water permeation software through soil (HYDRUS-2D [6], [7]) with an evolutionary multi-objective optimization (EMO) procedure to obtain some initial results.

In the remainder of this paper, we make a brief description of the SWRT technology achieved with impermeable membranes in Section II. Thereafter, we present the optimization problem formulation for finding optimal irrigation schedule and sizing and location of membranes for given soil properties, climatic conditions at the location, and crop being grown. The optimization involves optimizing multiple conflicting objectives. The integration procedure of an EMO methodology (NSGA-II [8]) with a numerical simulation software (HYDRUS-2D [6]) is discussed in also discussed in this section. Then in Section IV, we present initial results of our proposed integrated methodology. Results from three case studies are presented and the usefulness of the proposed integrated effort is discussed. Finally, Section V draws conclusions and highlights some promising future studies.

II. Subsurface Water Retention Technology (SWRT)

Sandy soil characterized by low water retention and high water permeability are challenging for sustainable crop production. Subsurface barriers were proposed as an effective mean to improve hydraulic properties of sandy soils. In the past, a number of materials were tested in their effectiveness in water barrier construction, including gel-conditioners, sediment and clay, and asphalt. While asphalt barriers demonstrated their long-term effectiveness in improving crop yields in sandy soils, their installations are costly. New polymer technologies offered replacement of labor and cost expensive asphalt barriers with technologically advanced, and very long-term affordable polyethylene membranes. To retain water at the root level, impermeable membranes are strategically placed at various depths below a plant's root zone to retain soil water, as shown in Figure 1. Recent studies have shown that the

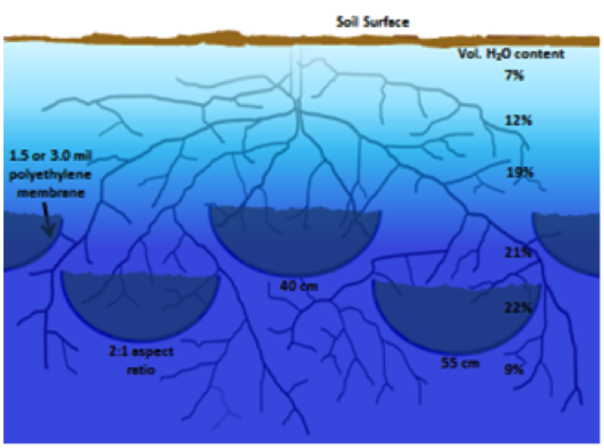

Fig. 1. Bowl-shaped membranes hold adequate water for plant roots.

membranes can retain up to 2.57-fold more plant-available water and nutrients within plant root zones of sandy soils dramatically reducing drought stress events by approximately 25 fewer short and longer-term drying cycles per crop season [5]. Proper spacing of the membranes also permits an internal drainage during excess rainfall and provides space for root growth. These new SWRT water saving membranes provide spaces for taproot growth among the membranes into depths greater than the membranes in a manner that maximizes production of cellulosic biomass and food products by 1.4-fold for vegetables to 3.38-fold for corn [5]. Following extensive laboratory testing, these newly designed SWRT membrane systems have surpassed their proof-of-concept during extensive tests in both the greenhouse large lysimeter [2], [9] irrigated field research during two contrasting seasons of the dry 2012 summer and wet 2013 spring in Michigan. SWRT-enhanced sand soils produced record yield levels of 20.4 metric tons per hectare in 2014.

While the SWRT is currently being used and the technology is being constantly improved by testing in controlled laboratory environment, there exist quite a few parameters which should be set properly to take the maximum advantage of the technology. Since it is expensive and time consuming to perform such parametric studies in a laboratory, there has been some research studies in which a mathematical model of the soil water flow is simulated using computational softwares, such as HYDRUS-2D [6]. Recently HYDRUS-2D model has been used for assessment of water losses in irrigated sandy soil with and without SWRT membrane [10]. Soil hydraulic parameters were obtained in HYDRUS-2D calibrations of water content dynamics measured during first six days of the large sand lysimeter irrigation experiments. Good agreement between simulated and measured water content dynamics indicated applicability of the HYDRUS-2D water fluxes in SWRT-modified soils.

In this paper, we propose an integrated approach in which membrane geometries and their subsurface location coupled with additional surface water irrigation schedule are optimized using an evolutionary multi-objective optimization method. However, the evaluation of such a solution is achieved using HYDRUS-2D software. We discuss this integration procedure in the next section.

III. Proposed Optimization of SWRT

In this section, we provide a detail account of our integration procedure. As mentioned above, our approach involves an integration of two computational approaches – EMO for optimizing membrane dimensions and their arrangement along with irrigation scheduling, and HYDRUS-2D for evaluating a membrane arrangement and water scheduling scenario to obtain the most economical as well as most energy efficient solutions.

It is assumed that the soil properties, climatic conditions including daily precipitation information for the specific farmland are available. The type of crop being grown is also assumed to be known. Figure 2 shows a sketch of the integration procedure between EMO and HYDRUS-2D software. The top left block illustrates the variables specifying the sizes and placement of membranes underground. A variable vector $\mathbf{x}$ denotes all necessary parameters for this purpose. The supplemental irrigation water added above ground is denoted by a time-varying variable $y(t)$. This specifies the amount of water to be added for the entire time span of the plant growth. The unit time can vary from an hour to a day to a week, depending on the precision needed in the final outcome. Thus,

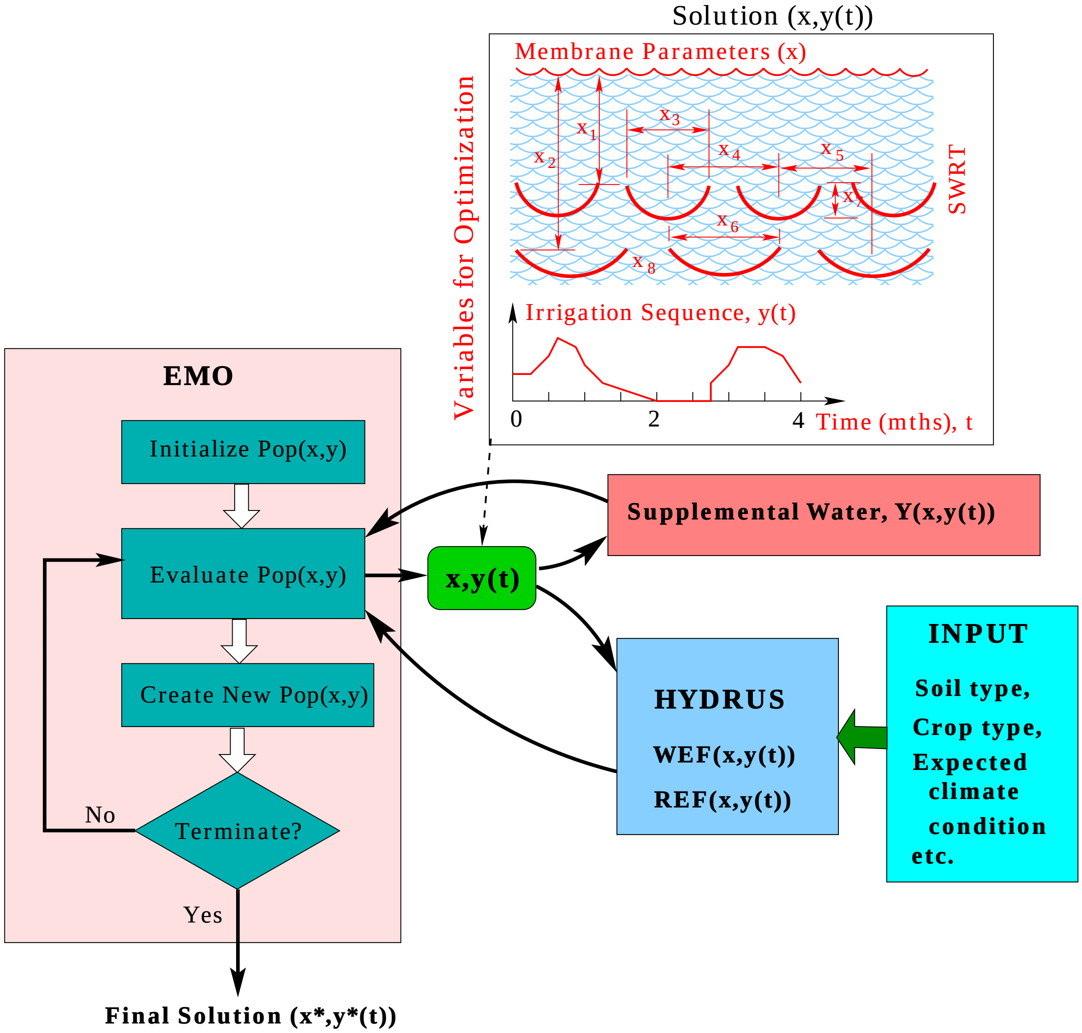

Fig. 2. The EMO-HYDRUS integration procedure is illustrated.

a combination of these two variable sets $(\mathbf{x}, y(t))$ indicates a solution to the overall optimization problem.

As in any optimization process, the next step is to determine a way to evaluate a solution. The SWRT optimization problem involves more than one conflicting objectives: (i) minimization of energy required for irrigation (this can directly proportional to the amount of supplied irrigation water, $Y(\mathbf{x}, y(t))$), (ii) maximization of water content at the membrane so that root tips get adequate water, (iii) maximization of water content at the complete root system from membrane to the start of the root system, etc. The first objective can be computed easily from the variable $y(t)$, however the evaluation of second and third objectives is not that straightforward and requires the use of a simulation software HYDRUS. Investigating the output parameters that can represent the above objectives adequately, we observe that HYDRUS-2D prints out certain properties from which we can compute the following two quantities: WEF$(\mathbf{x}, y(t))$, defined as the fraction of total irrigation water that was not drained below the membrane installation depth and water uptake efficiency REF$(\mathbf{x}, y(t))$, defined as the ratio between actual and potential water uptake by crop roots. Figure 3 shows the finite element mesh generated for simulating water flow in HYDRUS-2D software. The boundary conditions are chosen so as to simulate the two-layer membrane placement shown in Figure 2 by a repeated pattern of the geometry shown in Figure 3. The objective function formulation is given in the following subsection.

A. Objectives and Variables Used in This Study

In this study, we consider the following two objectives to understand the interactions between the second and third objectives: 1) maximization of water use efficiency (WEF) and 2) maximization of root water uptake efficiency (REF). When REF and WEF values are close to one, this means adequate water is available at the membrane and also at the complete root system thereby favoring conditions for crop growth and zero losses of irrigation water for deep percolation.

To simplify the variable handling, first we use $y(t)$ as the only variable for our EMO-HYDRUS-2D integration task, thereafter we consider both sets of variables $(\mathbf{x}, y(t))$ in a special way. For the first case, we fix the membrane configuration and vary the surface water irrigation schedule with time for minimizing the above-mentioned two objectives. To

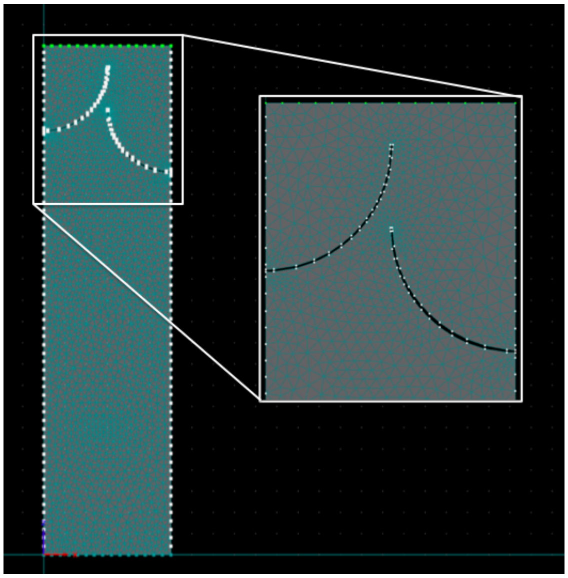

Fig. 3. The geometry and enmeshment of the HYDRUS-2D model with the SWRT membranes installed at the depth of 20 and 30 cm of sand and the aspect ratio (AR) of 2:1.

simplify the matters further, we use a fixed flow rate (simulating the use of a fixed sprinkler system), but only control the duration (t_{dur}) of water supply per day. For the second case, due to the complexities associated in handling changing configurations of membranes, we use a finite number of pre-arranged configurations and let the optimization algorithm finds the appropriate ones as final optimized solutions. Thus, the optimization problem formulation becomes as follows:

$$\begin{aligned} \text{Max.} \quad & f_1(AR, t_{dur}) = WEF(AR, t_{dur}) = 1 - \frac{S_{drain}}{S_{irr}}, \\ \text{Max.} \quad & f_2(AR, t_{dur}) = REF(AR, t_{dur}) = \frac{CumQR}{CumQRP}, \\ \text{Subject to} \quad & AR \in AR_{supplied}, \\ & t_{\min} \leq t_{dur} \leq t_{\max}. \end{aligned} \tag{1}$$

Here, $CumQR$ is the root water uptake and $CumQRP$ is its potential value. The aspect ratio (AR) of the membranes are used as discrete variable and a finite number of options specified in the supplied set $AR_{supplied}$ are considered. The surface water supply duration is varied between specified minimum and maximum values. Here, we use $t_{\min} = 0.021$ and $t_{\max} = 0.667$ in all our simulations.

The enmeshed HYDRUS-2D model used for the optimization study is shown in Figure 3 for a membrane with $AR = 2:1$. The width and the height of the domain is 30 cm and 120 cm, respectively. Half of the membrane geometries (symmetry boundary condition is applied), with 2:1 aspect ratio, installed at depths of 20 and 30 cm. Atmospheric boundary conditions (i.e. precipitation and evaporation) is defined at the soil surface (green dotted line). Irrigation is also applied as a boundary condition at the surface. Free drainage boundary condition is defined on the nodes at the bottom line. The irrigation flow rate is fixed at 24 cm/day.

IV. Results and Discussions

We make a systematic study and present our results in this section. Three cases are considered. Cases-1 and 2 consider the $y(t)$ variable only, whereas Case-3 considers both types of variables. On a Windows 7 Professional OS, 4th generation Intel Core i7 Extreme Edition CPU, 16GB 1600MHz RAM computer, a single HYDRUS-2D simulation takes approximately 1 minute depending on the number of irrigation events. However, some runs takes about 2 minutes as well. Thus, this problem is considered computationally expensive, taking about one full day of computations on the above computer to complete one optimization simulation involving about 1,000 evaluations. In all simulations, we have used NSGA-II [8] with the following parameters: population size=20, maximum number of generations=50, SBX recombination with p_{cross}=0.9 and η_c=10, and polynomial mutation with p_m=0.5 and η_m=20.

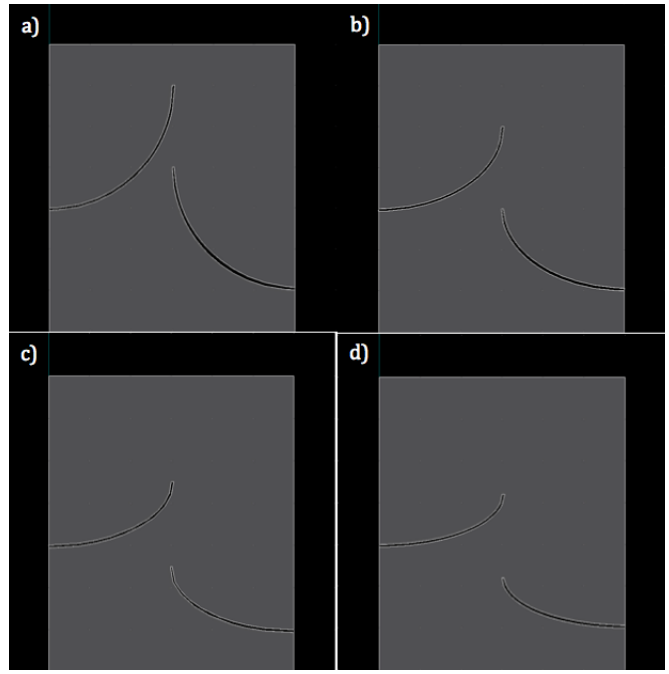

Fig. 4. Four membrane designs with different aspect ratios, i.e. a) 2:1, b) 3:1, c) 4:1, and d) 5:1, respectively.

A. Case Study-1

In this case, the 2:1 aspect ratio membrane system is fixed and t_{dur} is used as a variable. Two optimization studies are compared with each other: with and without membranes. This comparison is made to investigate the effect of using the SWRT in retaining water at the root level.

Figure 5 shows the obtained trade-off solutions. The blue circles mark the trade-off objective values for the membrane case. First of all, it is clear that there is a trade-off between the two objectives: WEF and REF. While a large water retention (close to $WEF = 0.8$) is possible, but it comes only the expense of relatively low root uptake water, $REF \approx 0.88$, and vice versa. Secondly, since both objectives are to be maximized, the WEF-REF values obtained for the membrane based irrigation (blue circles) are better than those without membrane (black circles).

Figure 6 shows the respective t_{dur} values for each of the two scenarios. It is evident that the optimized duration for supplying surface water for membrane-based irrigation is

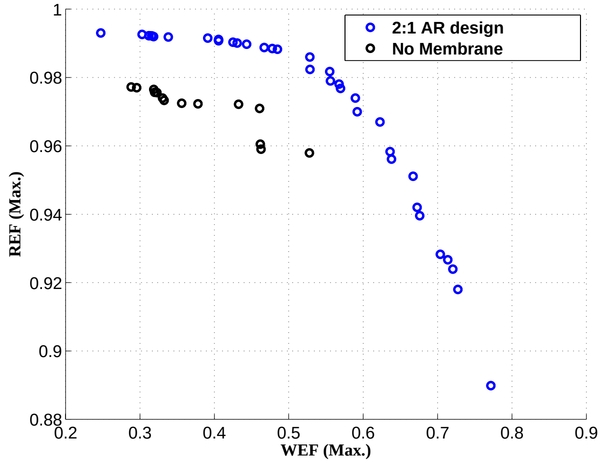

Fig. 5. Efficient fronts obtained for membrane-based irrigation with $AR = 2:1$ membranes (blue) and without any membrane (black).

much smaller than an irrigation without any membrane. Since membrane-based irrigation is able to retain water, less water needs to supplied at the surface level. It is clear that the amount of supplied water for the membrane-based irrigation can be as high as about 7 times less than that without any membrane. This indicates a remarkable saving in water and subsequently the required energy to supply the needed water.

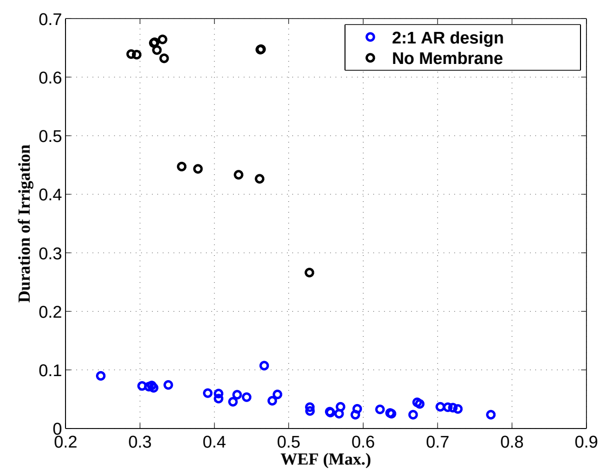

Fig. 6. Duration of irrigation values of the the obtained trade-off solutions using membrane with 2:1 aspect ratio (blue) and without membranes (black).

B. Case Study-2

Having shown the advantage of using the SWRT based irrigation, we now investigate the effect of sizing of the membranes on the two objectives used above. Four different aspect ratios of the membranes are considered one at a time, $AR_{supplied} = \{2:1, 3:1, 4:1, 5:1\}$. NSGA-II parameters are identical to those used above.

Figure 7 plots all four trade-off fronts in different colors. Each individual plot produces a respective trade-off between

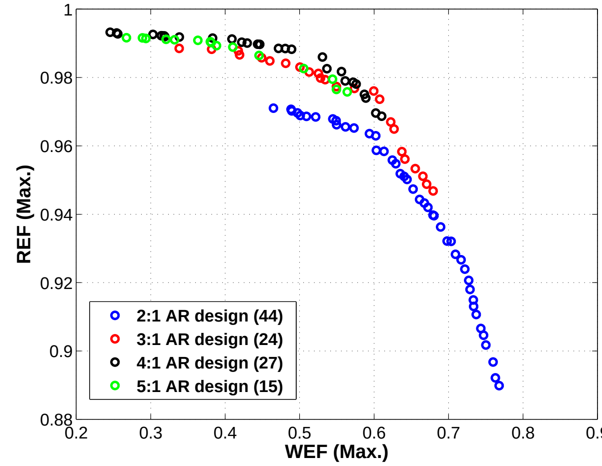

Fig. 7. Four efficient fronts obtained with NSGA-II applied respectively to four different membrane configurations: AR of 2:1, 3:1, 4:1 and 5:1. The number of solutions found for each configuration is marked in parenthesis.

WEF and REF values. However, following interesting observations can be made.

1) The smallest AR configuration ($AR = 2:1$) is most efficient for maximizing WEF-objective, meaning that if the water content inside the membranes is the primary concern, the use of 2:1 membranes are the best. This is because 2:1 membranes are deepest among all four membranes considered in this study and is able to hold maximum amount of water.
2) With the increase in aspect ratio, the trade-off solutions care more about maximizing REF-objective. This is because with the membranes being more flat, membranes do not absorb more water, rather more water is retained in the whole root uptake system.
3) A very interesting observation is made next. Although the above argument may indicate that $AR = 5:1$ will produce the most REF-efficient scenario, it is observed that all solutions with this configuration (green circles) are dominated by $AR = 4:1$ configuration. This indicates that there is a limit to the flatness of the membranes that will allow the water to be retained on top of the membranes. Too much flatness results in a poor REF value.

These are interesting yet useful observations which the membrane designers must keep in mind.

Next, we plot the t_{dur} for each of the four configurations in Figure 8. Another interesting observation is made here. In all cases, clearly, an increase in REF comes from an increase in t_{dur}. That is, more surface water must be supplied to achieve a higher root uptake efficiency. Since the soil used in this study is *sandy*, the surface water quickly gets permeated at the membrane. Thus, if more water needs to be retained at the whole root system, more surface water needs to supplied. In Figure 9, we replot the t_{dur} versus WEF solutions and fit a line by ignoring the outliers. The following relationship is observed:

$$t^*_{dur} = 0.1832 - 0.2066\, WEF^*. \quad (2)$$

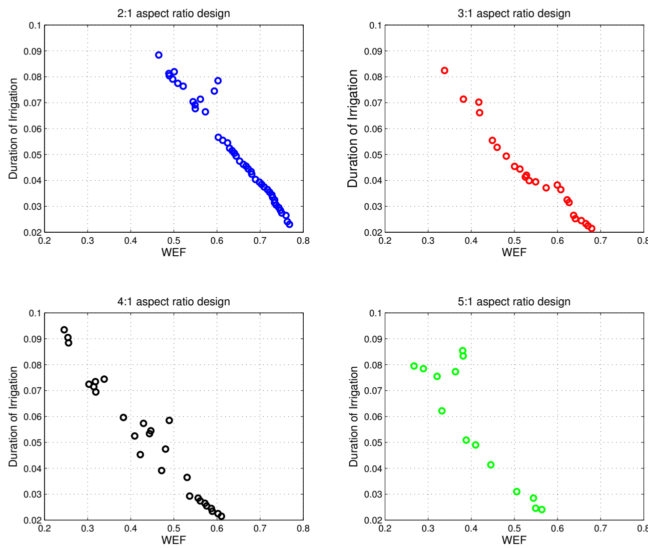

Fig. 8. The duration of irrigation is plotted with WEF for optimized trade-off solutions obtained four different membrane configurations independently.

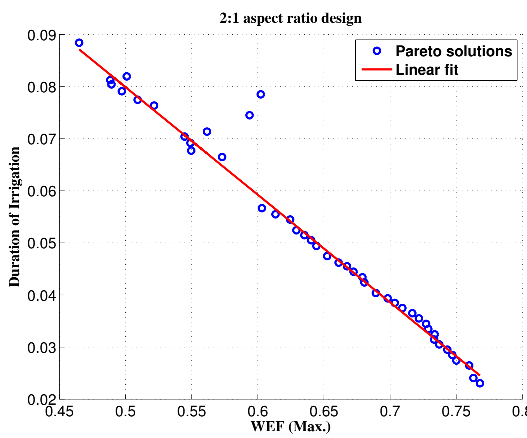

Fig. 9. Linear fit for the optimal duration of irrigation values as a function of WEF for $AR = 2:1$ membranes.

The relationship indicates that to have 10% more water efficiency at the membrane, 2% less water needs to be supplied at the surface. The extraction of such key solution principles from obtained optimized trade-off data was first proposed in 2003 [11] and later named as the task of *innovization* [12]. Since these principles are properties derived from high-performing optimal trade-off solutions, they provide valuable information and insight about 'what makes a solution optimal?'. In this precision irrigation task, a farmer can use the above relationship and compute the duration of surface water supply from a desired water retention at the membrane for a particular crop. The constants of the relationship will probably depend on the parameters which have been kept fixed during the optimization process, such as soil properties, climatic conditions and crops being produced. The ability of finding such useful information remains as the hallmark of performing the multi-objective optimization task described in this paper.

If we are interested in getting a direct relationship between t_{dur} and REF, we can fit a relationship as well. For $AR = 2:1$ solutions, we find the following relationship:

$$\begin{aligned} t^*_{dur} &= 2136.2 - 7154.1REF^* + 5882.8REF^{*2} \\ &\quad + 4092.3REF^{*3} - 7908REF^{*4} + 2951REF^{*5}. \quad (3) \end{aligned}$$

Figure 10 shows the obtained points and the fitted relationship as a fifth-order polynomial. The important matter is that the relationship between these two entities are monotonic and non-linear. A fifth-order fit provides a good relationship. There exists a critical $REF^{cr} = 0.95$, beyond which surface water must have to be supplied at a much larger rate than achieving a REF value below 0.95. In other words, an expectation of $REF > 0.95$ may not be energy-efficient. Furthermore, a farmer is in a position to use the relationship to find optimal duration t_{dur} for any desired REF value.

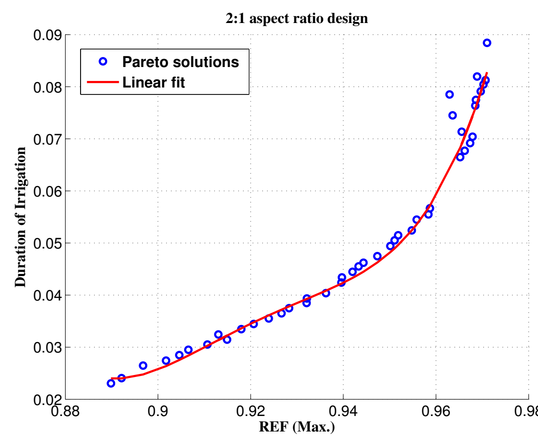

Fig. 10. Fifth-order polynomial fit for the optimal duration of irrigation values as a function of REF for $AR = 2:1$ membranes.

C. Case Study-3

In Case Study-2, we have independently optimized each membrane configuration and combined all four results together to find their relative importance. In this case study, we consider all four configurations as a part of a single optimization and keep AR parameter also a variable. Since there are more variables in the problem, we use a population of size 40 but keep all other NSGA-II parameters the same as before.

Figure 11 shows the trade-off solutions obtained by NSGA-II. It is interesting to note that $AR = 5:1$ is absent in the final optimized trade-off front. This was also found in Case Study-2. The contribution of each AR configuration is clearly shown by marking different AR configurations using different colors. Larger WEF values are achieved with 2:1 configuration and larger REF solutions are achieved with 4:1 configuration. But a good trade-off between REF and WEF can be achieved with 3:1 configuration.

The trade-off front shown in the figure clearly indicates a 'knee'-like solution at around $WEF = 0.6$ (with $REF = 0.975$). A solution having a larger WEF comes with a sharp drop in REF value and a solution having a larger REF comes with a deep drop in WEF value. Thus, from a good trade-off

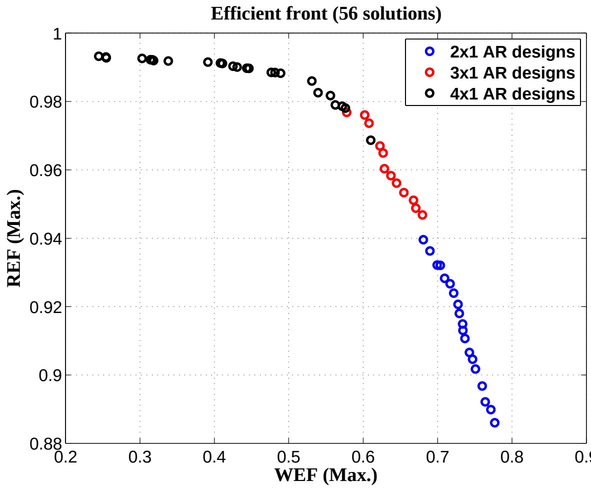

Fig. 11. Trade-off solutions using NSGA-II run with four configurations of the membranes and time duration of water supply as variables.

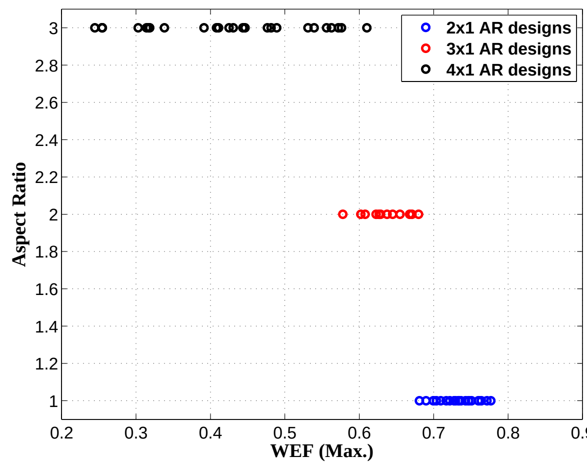

Fig. 13. The aspect ratio values versus WEF values of the solutions in the efficient front are drawn above. Designs with different aspect ratios are indicated with different colors.

between REF and WEF, this knee solution may remain as a likely choice for decision makers.

Figure 12 shows the respective t_{dur} values for obtained trade-off solutions of Figure 11. It is clear that large WEF value comes from a small duration of surface water supply for all configurations. However, different configurations have a different effect on REF and WEF. For the same t_{dur} of water supply (say $0.03 \times 24 \times 60$ or 43.2 min per day), a 2:1 membrane configuration is able to have 73% WEF, whereas a 4:1 membrane configuration has only 54% WEF. However, the respective REF values are 91% and 98.2%, respectively. Somewhat linear relationship between optimal t_{dur} and WEF for each configuration is clear from the figure.

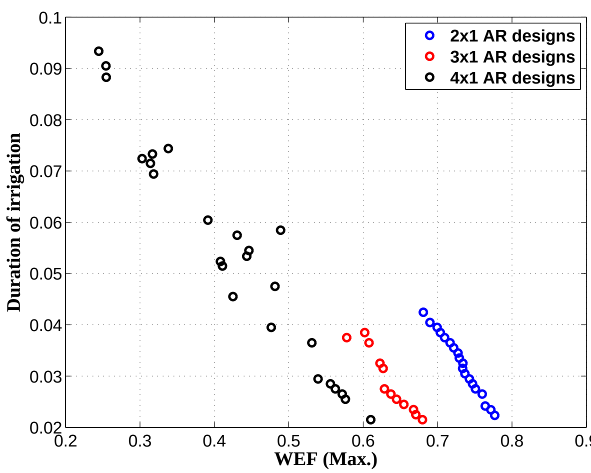

Fig. 12. The duration of irrigation values versus WEF values of the solutions in the efficient front are drawn above. Designs with different aspect ratios are indicated with different colors.

Finally, Figure 13 shows the respective aspect ratio (AR) for each trade-off solutions. It is clear that largest WEF values are achieved from 2:1 configurations and smallest WEF (or highest REF) values are achieved from 4:1 configurations.

V. Conclusions and Future Work

In this paper, we have made a multidisciplinary computational approach in which recent advances in evolutionary multi-objective optimization (EMO) field is used to optimize subsurface water retention technology (SWRT) based precision irrigation system. The dynamics of water flow in SWRT is simulated using a state-of-the-art HYDRUS-2D software which is an external input-output file-driven system. Each simulation under HYDRUS-2D takes at least a minute of CPU time on a standard computing system, thereby causing a modest application of an EMO more than a day.

The SWRT based precision irrigation system involves two types of variables: (i) fixed design related variables involving sizing and location of a series of polyethylene membranes and (ii) time-varying surface water supply schedule. Both types of variables cause implementational difficulties, requiring a change in the input file for any little change in the variable values. By using a discretization method for the first static design variables, we have been able to integrate an EMO methodology (NSGA-II) and HYDRUS-2D to find optimized trade-off solutions for three different case studies.

The simulation results have generated a number of interesting conclusions:

- It has been clearly observed that a SWRT-based irrigation is better able to retain surface water both at the root level and also at the membranes for a consistent supply of water to the plant roots.
- A larger root uptake water content requires a larger supply of surface water.
- A larger water content at the membranes require a relatively smaller supply of surface water.
- Each of the above has been quantified for an optimal use.
- The best configuration for achieving a larger root water uptake is to use shallower membranes.

- The best configuration for achieving a larger membrane water content is to use deeper membranes.
- A membrane having an arbitrarily large aspect ratio is not beneficial for either root water uptake or membrane water efficiency.

The above outcome of our initial study on EMO for precision irrigation problem is encouraging and motivating us to make a further and deeper investigation. In the future, we plan to repeat the study for different types of soil conditions, such as sandy, sandy loam and clay type; for different climatic conditions, such as a land with less and more rainfall; and for different crop types. As some crops have deeper roots than others, the outcome of an optimization run is expected to be different in each case. If the same land and same membrane configurations are to be used for different crops during a year, a compromise configuration and location of membranes must be found using an optimization method. We also plan to consider more membrane configurations and include their depth from the surface as new variables. This study has considered two objectives related to the water content at different levels, but other objectives such as maximization of plant growth as a direct outcome of water retention would an interesting objective to include. HYDRUS-2D software also allows to simulate the permeation of nutrients through soil and an adequate supply of nutrients at the root level is equally essential as water. We plan to include one or more objectives related to maximum retention of root level nutrients as an indicator of plant growth. Although HYDRUS-2D has been used in this study, HYDRUS-3D [13] would enable a realistic three-dimensional treatment of the water and nutrient flow. Due to the increase in simulation time, we plan to use meta-modeling based EMO methods for handling these future studies.

Thus, it is clear that this pilot study just scratches the surface of a plethora of more realistic studies involving an EMO to precision irrigation system design problem. If the above-mentioned tasks are achieved, it will be a triumph for computational tools such as EMO in helping to minimize water and energy requirements for precision irrigation. The tasks should also produce valuable knowledge which may remain as useful 'thumb-rules' for achieving good irrigation practices.

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