Field and modeling study of sprinkler irrigation for season long vegetable production in the Yuma Valley Irrigation District

By

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Executive summary

Solid set sprinkler systems are commonly used to irrigate crops worldwide. In the Yuma Valley Irrigation District solid set sprinkler systems are increasingly used for season long vegetable production. Existing systems were primarily designed to provide supplementary irrigation (mainly for environmental control purposes) during the early part of the vegetable growing season. However, with season long sprinkler operation, the objective of irrigation is not only providing adequate water supply for environmental modification for the first few weeks of stand establishment, but also applying it efficiently and uniformly. Hence, the performance of sprinkler systems designed primarily for supplementary irrigation may need to be evaluated in light of the requirements of season long use. In the current study (which has both field and modeling components), irrigation performance is evaluated in terms of irrigation application uniformity.

A typical field-scale solid set sprinkler system in the Yuma Valley Irrigation District consists of an open pipeline network of aluminum pipes, commonly obtaining its supply from a lined field supply canal. Water is pumped (often using centrifugal pumps) from the canal into a main with equally spaced multiple outlets, each supplying irrigation water to a lateral. Valves are used to control the supply to individual laterals. Each lateral is fitted with regularly spaced riser pipes supporting a sprinkler head, which distributes water over the irrigated field in the form of precipitation. There are two types of field layout configurations typically used in the Yuma Valley Irrigation District: The most common one consists of a mainline installed across the head end of the field supplying irrigation water to a line of laterals installed on one side of the main, described here as a system with single-line laterals layout configuration (Zerihun and Sanchez, 2012). Another widely used field layout consists of a mainline installed in between two adjacent irrigated fields, or somewhere within an irrigated field, and supplies irrigation water to two sets of laterals, each installed on either side of the main. Such a system is referred here as one having double-line laterals layout configuration. With this layout each set of laterals irrigate either a fraction of the field or each of the adjacent fields, as the case may be. In the irrigated fields of the Yuma Valley, land surface slopes are typically flat; hence they have negligible effect on system hydraulics. Soils in the area are relatively heavy (with texture varying from the silt loam to silt clay range) and sprinkler irrigation is often light and frequent, which is well suited to the relatively shallow rooted high value vegetable crops grown in these fields.

Field-scale sprinkler irrigation system uniformity can be evaluated through on-site evaluations. A commonly used field technique for the evaluation of a solid set sprinkler irrigation system application rates and distribution uniformity involves the installation of a test-plot between two adjacent laterals with overlapping sprinkler application patterns (Martin et al., 2007a; Keller and Bliesner, 1990; Cuenca, 1989). Typically, a test-plot consists of a rectangular area, with dimensions equal to sprinkler and lateral spacing, and is populated with an array of rain gages arranged in grid squares. In some of the field evaluations, pertinent meteorological data (mainly wind speed and direction) can be measured at regular time intervals. At the end of a field evaluation, precipitation depths collected in each of the rain gages in a test-plot are recorded and used in test-plot scale uniformity calculation. Test-plot scale irrigation uniformity evaluations can be replicated over an irrigated field, to take into account the effects of spatially variable factors on irrigation uniformity, based on which field-scale uniformity can be estimated.

In this study, two field evaluations were conducted in a grower’s farm in the Yuma Valley Irrigation District. The field-scale sprinkler system used in these evaluations has single-line laterals layout configuration. During the field evaluations, plot scale uniformity tests were performed at preset locations in the irrigated field. The test-plot scale application uniformities were scaled up to field-level through averaging. The results of the field study show that measured field-scale irrigation uniformities are high (with field-scale Christiansen’s uniformity coefficient, UCC, of about 0.75 and 0.90 and low-quarter distribution uniformity, DU_{lq}, of 0.69 and 0.85). These values are in the moderately high to higher end of the range recommended for solid set sprinkler system design (Keller et al., 1980). The field evaluations were conducted under low wind speed conditions (with average wind speeds during the field tests not exceeding 1.8m/s). In an earlier study conducted in a different sprinkler irrigated farm, similarly high field-scale irrigation uniformity was obtained: UCC = 0.85 and DU_{lq} = 0.78 (Zerihun et al., 2011). Additional sprinkler irrigation system field evaluations were conducted in the Maricopa

Agricultural Center of the University of Arizona. The sprinkler system used in this study has a double-line lateral layout configuration. Five field evaluations were conducted under comparable hydraulic and ambient weather conditions (wind speed ≤2.5m/s). Test-plot scale UCC and DU_{lq} values vary between 0.75 to 0.92 and 0.69 to 0.88, respectively; with field-scale average UCC of 0.86 and DU_{lq} of 0.78. The Maricopa study was conducted in an experimental sprinkler system specifically set up for the study described here and it is smaller than a typical field-scale sprinkler system in the Yuma Valley. Hence, the results described here are significant only to the extent that sprinkler systems with sufficiently large lateral and mainline diameters, to keep energy loss to a minimum, can attain high levels of irrigation uniformity provided the system is well maintained, properly installed, operated under low wind speed conditions, and application rate is sufficiently small to make sure that there is no surface runoff. In addition, hydraulic evaluations (consisting of pressure head and discharge measurements along laterals) were conducted as part of the Maricopa study. The hydraulic data was primarily used for evaluation of a field-scale sprinkler irrigation hydraulic model, developed as part of the current study, but it also provided a qualitative measure of the effects of system hydraulics on application uniformity.

Field studies can provide a more realistic evaluation of irrigation performance. However, mathematical models can offer a much more flexible and inexpensive alternative for developing optimal sprinkler irrigation system design recommendations. Flow in a field-scale solid set agricultural sprinkler system can be considered steady without loss of generality. Hence, pressure head and discharge distribution along a lateral or mainline can be modeled through the application of the energy conservation and continuity equations for steady incompressible flow (Granger, 1995; Larock et al., 2000; Miller, 2009). Because of limitations in computational resources, in the past analytical solutions of these equations derived based on a set of simplifying assumptions were commonly used in the hydraulic analysis of sprinkler systems. Christiansen (1942) approximated the friction head loss in a sprinkler lateral as the product of the friction head loss in an equivalent flow through pipe (computed with a suitable friction head loss equation) and a friction reduction factor. Various improvements and enhancements have been proposed to the basic approach of Christiansen to allow for increased flexibility in terms of the location of the first sprinkler with respect to the lateral inlet, provisions for computing friction head loss in tapered laterals, and in lateral with residual outflow (Jensen and Fartini, 1957; Keller and Bliesner, 1990; Anwar, 1999; Vallesquino and Escamilla, 2002; Yitayew, 2009). Current advances in computing allow the implementation of numerical procedures, not limited by many of the assumptions listed above, to describe the field-scale hydraulics of sprinkler systems. Considering sprinkler laterals and mains as manifolds (pipes with multiple outlets of known hydraulic characteristics), a rigorous and flexible formulation of the field-scale sprinkler system hydraulic problem can be obtained by coupling the energy equation for each lateral/main segment with the continuity equation at a node. The resulting set of equations is then solved iteratively starting from the distal end sprinkler/mainline outlet and moving sequentially upstream along the lateral/mainline (e.g., Larock et al., 2000; Miller, 2009). An appropriate interpolation scheme can then be used as an interface to couple the numerical solutions of the lateral and mainline hydraulic equations (Zerihun and Sanchez, 2012).

Mathematical models of sprinkler irrigation system networks exist (e.g., de Andrade and Allen, 1999; AEI Software, 2011). These models have the capability to simulate the hydraulic characteristics of a field-scale sprinkler system. However, their emphasis is on hydraulic analysis of large scale pressurized agricultural water distribution networks. A model for the optimal design and management of field-scale sprinkler irrigation system requires the coupling of a rigorous field-scale hydraulic model with a droplet-dynamics submodule (for computing the pattern of precipitation around a sprinkler, e.g., Playan et al., 2009) and a soil hydraulic model (for simulating subsequent infiltration and soil water flow processes, e.g., Simunek et al., 2009). The development of a computationally efficient and robust model with such a capability remains a challenge.

As a step toward the development of a fully coupled field-scale sprinkler irrigation model, a rigorous and flexible mathematical model for the hydraulic characterization, simulation, and design of a field-scale solid set sprinkler system is developed. The basic numerical algorithms used for modeling the hydraulics of a field-scale solid set sprinkler system with single-line laterals layout configuration were developed and evaluated though comparison with field data, as part of an earlier study

(Zerihun and Sanchez, 2011). Further development and enhancement of the hydraulic model has been performed within the framework of the current study (Zerihun and Sanchez, 2012), which include: (1) The formulation and numerical solution of the hydraulic equations for a sprinkler system with double-line laterals layout configuration; (2) An interpolation scheme, based on cubic splines, was developed and incorporated into the current version of the model as an interface for coupling the numerical solutions of the lateral and mainline hydraulic equations; (3) A one-dimensional optimization algorithm is developed and incorporated into the hydraulic simulation and design functionalities of the model; (4) Enhancements were made to earlier version of the model in order to accommodate field layouts with irregular boundaries (variable lateral lengths); and (5) A new functionality for computing test-plot scale and field-scale sprinkler irrigation uniformity from field data is developed.

The model can be used to conduct hydraulic analysis of field-scale sprinkler systems with uniform or spatially variable hydraulic, geometric, and topographic characteristics. Because of the scope of the study, currently model development is limited to field-scale hydraulics. However, the objective is to eventually couple the hydraulic model with soil water flow and droplet dynamics models, thereby developing a modeling capability for a complete characterization of the field-scale irrigation performance of a solid set sprinkler system. With support from the USBR, a follow up study aimed at developing a droplet dynamics model capable of simulating precipitation patterns around a single sprinkler and exploring possibilities for coupling it with the field-scale hydraulic model is being undertaken.

The component of the mathematical model, developed for hydraulic analysis of field-scale sprinkler systems with single-line laterals layout configuration, was evaluated with field data as part of a previous study. The results of the study showed that model predictions compare well with field data, suggesting that the numerical algorithms of the hydraulic model for systems with single-line laterals is accurate. In this study, a limited evaluation of the model functionality developed for the hydraulic analysis of systems with double-line lateral layout configuration has been conducted through comparison of model output with field data. The results show that the performance of the model is satisfactory. In addition, the model is used to evaluate the hydraulic characteristics of the sprinkler system used in the field study. It is also used to evaluate the sensitivity of the hydraulics of the system to changes in hydraulic, geometric, and topographic variables. Example simulations highlighting the practical application of the model in the hydraulic analysis of field-scale sprinkler systems with spatially variable geometric and topographic characteristics are presented.

This report consists of six chapters. Chapter 1 presents the introductory section of the report, which includes project objectives. Chapter 2 briefly reviews the sprinkler irrigation literature. A description of a typical solid set sprinkler system used for season long vegetable production in the Yuma Valley Irrigation District is presented in Chapter 3. Chapter 4 discusses the methodology used in the field and modeling studies. The results of the field and modeling studies are presented and analyzed in Chapter 5 and Chapter 6 presents a summary of the results and recommendations for further study.

Chapter 1. Introduction

Furrow irrigation has been the primary irrigation method for row crops, including vegetables, in the low desert valleys of the southwestern United States. However, during the first few weeks of the vegetable cropping season it is customary to use solid set sprinkler systems for stand establishment purposes, with all subsequent irrigations being provided by furrow irrigation. The main aim of sprinkler irrigation for stand establishment purposes is environmental modification (keeping the soil cool and wet enough) for the seedling to emerge and establish itself. Typical system configurations and operation guidelines for the supplementary sprinkler systems were developed primarily based on broad recommendations of system component manufacturers and growers' experience and given the short duration and the purpose of irrigation, achieving high levels of efficiency was not considered critical.

More recently, there has been an expansion in the use of solid set sprinkler irrigation in the Yuma Valley Irrigation District for season long vegetable production with the view of increasing irrigation water use efficiency. With season long sprinkler use, the objective of irrigation is not only providing adequate water supply for environmental modification for the first few weeks of stand establishment, but also applying it efficiently and uniformly. Hence the performance of sprinkler systems developed primarily for supplementary irrigation applications may need to be evaluated in light of the requirements of season long operation.

In 2010 the Yuma Agricultural Center of the University of Arizona with support from the Arizona Specialty Crops Council have conducted field and modeling study aimed at evaluating the field-scale irrigation application uniformity of a typical solid set sprinkler system in the Yuma Valley (Zerihun et al., 2011 and Zerihun Sanchez, 2011). Although the study was primarily concerned with the development of equipment and methods for field-scale sprinkler irrigation evaluations for application in the Yuma Valley Irrigation District, there are important results stemming from it. The results show that considering the topographic, geometric, and hydraulic attributes of the sprinkler system used in the study and the prevailing irrigation practices, high field-scale irrigation application uniformities (Christiansen's uniformity coefficient of 0.85 and a low-quarter distribution uniformity of 0.78) can be achieved provided the sprinkler system is operated under conditions of relatively low wind speed. In addition, as part of this study a mathematical model that can be used in the hydraulic analysis of a field-scale sprinkler system with single-line lateral layout configuration was developed and a limited evaluation of the model through comparison with field data suggests that the model is accurate. The hydraulic measurements and modeling studies show that the hydraulic design of the sprinkler system of the evaluation farm is robust (i.e., the field-scale irrigation application uniformity should be virtually insensitive to changes in pipe hydraulic resistance characteristics and field slopes within reasonable ranges). However, considering the limited nature of the study cited above, these results may not be typical for the Yuma Valley Irrigation Districts as whole. Hence, additional studies, taking into account the variations in terms of system hydraulics and irrigation practices, are needed to evaluate the average field-scale sprinkler system irrigation uniformity levels and ranges of variations. In addition, the hydraulic model should undergo significant further developments in order to enhance its flexibility in terms of variability in field geometry and system layout configurations that it can accommodate and the mathematical rigor of the numerical solution.

The overall objective of the study reported here is to conduct irrigation uniformity field evaluations, in farms that are used for season long vegetable production in the Yuma

Valley Irrigation District, and perform hydraulic modeling studies. Specific objectives are: (1) To conduct additional irrigation field evaluations to infer estimates of application uniformity levels of field-scale solid set sprinkler irrigation systems in the Yuma Valley; (2) To develop numerical algorithms for the hydraulic analysis of field-scale sprinkler systems with double-line laterals layout configuration and refine and enhance the numerical rigor of the existing model; (3) To evaluate the model through comparison with field data; and (4) Highlight the practical application of the model in the hydraulic analysis of field-scale sprinkler systems with single-line and double-line laterals layout configurations and spatially variable geometric and topographic attributes.

Chapter 2. Literature review

A brief review of the sprinkler irrigation literature, as it relates to systems used for season-long vegetable production in the Yuma Valley Irrigation District, is presented in this section. The review highlighted herein was, for the most part, originally presented in a previous project report by the same authors (Zerihun et al., 2011) and is reproduced here with slight changes.

2.1 Sprinkler irrigation systems

Sprinkler irrigation is one of the most widely used methods of irrigation water application to croplands worldwide. Compared to surface irrigation systems, initial capital expenditure and running costs of sprinkler irrigation systems tend to be substantially higher (Keller and Bliesner, 1990). However, if properly designed and operated sprinkler systems can apply irrigation water at much higher levels of uniformity and efficiency. They are also better suited for applying light and frequent irrigations to shallow rooted high value horticultural crops, such as vegetables. Sprinkler systems are adaptable to a wide range of soil and topographic conditions, are amenable to site specific applications of both water and agricultural chemicals, and are well suited to automation reducing labor requirement considerably. Although sprinkler irrigation is primarily used to supply water to meet crop consumptive use needs, it is also used for environment control and modification purposes, such as frost protection and soil cooling in arid climates. Orchards (grapes, citrus, and most tree crops) can be sensitive to sprinkler irrigation with moderately saline water (Keller and Bliesner, 1990).

There is a wide array of sprinkler system types with varying system cost, adaptability in terms of soil, topography, crop, and irrigation performance (Keller and Bliesner, 1990; Cuenca, 1989). Field-scale sprinkler irrigation systems can be grouped into: solid set, periodic move, and continuous move systems. A solid set sprinkler system is one in which all the system elements, including the main and laterals, remain stationary at a set position at least during an irrigation season. Periodic-move systems consists of laterals, and possibly a mainline, that remain stationary at a set position during an irrigation event, but are moved from one set position to another in an irrigation cycle. A continuous-move system consists of system components that are in continuous motion during operation. The type of system widely used in the Yuma Valley for season long vegetable production (and is of interest herein) is the solid set system.

2.2 Solid set sprinkler irrigation system

Solid set systems have enough number of laterals and sprinklers to cover the entire irrigated field, hence they are the most capital intensive sprinkler systems. However, these systems are highly amenable to complete automation and labor cost is typically low, especially compared to periodic move systems (Keller et al., 1980). Considering optimal management and the same climatic conditions, solid set systems can attain a slightly higher irrigation performance compared to periodic-move systems (Keller et al., 1980). Solid set systems can be applied to wider ranges of topographic, crop, and soil conditions compared to other sprinkler systems. A typical solid set sprinkler irrigation system consists of an open pipeline network to convey and distribute irrigation water over the irrigated field. Figure 1 shows the schematics of such a system with its components. The system components are a water source, a pump, a mainline to convey irrigation water from the source across the irrigated field and distribute it among a series of pipes (laterals) that often run perpendicular to the mainline itself. Depending on available flow the field can be irrigated in a single set or in more than one set and valves are used to control the flow into individual or a group of laterals constituting an irrigation set.

2.2.1 System layout

The layout design of a solid set sprinkler system consists of matching the configuration of an open pipeline network with the geometry and topography of a field such that the cost of the system is minimized. In practice, the selection of sprinkler system layout does not involve optimization algorithms. Instead, a set of rule-of-thumb criteria, developed primarily with the objective of broadly balancing the conflicting needs of higher uniformity and lower system cost, are used to determine the relative orientations of the mainline and laterals. The mainline consists of a larger diameter pipe and carries much larger discharge than the laterals, hence it is more expensive than the laterals. The layout should therefore be selected such that the mainline is not too long and when possible the mainline should be positioned in the field such that the laterals are installed on both sides of it. In a field with uniform moderate slope, it is recommended that the mainline runs across the head end of the irrigated field, feeding a single-line of laterals installed on one side of the main. On the other hand, in a field with irregular topography, the mainline can be run along the ridge where elevation differences are minimal, supplying water to two sets of laterals. Laterals should preferably be installed down slope so that the friction head loss along the lateral will be compensated by gravity, resulting in a more uniform irrigation application along the lateral while maintaining a lower system cost.

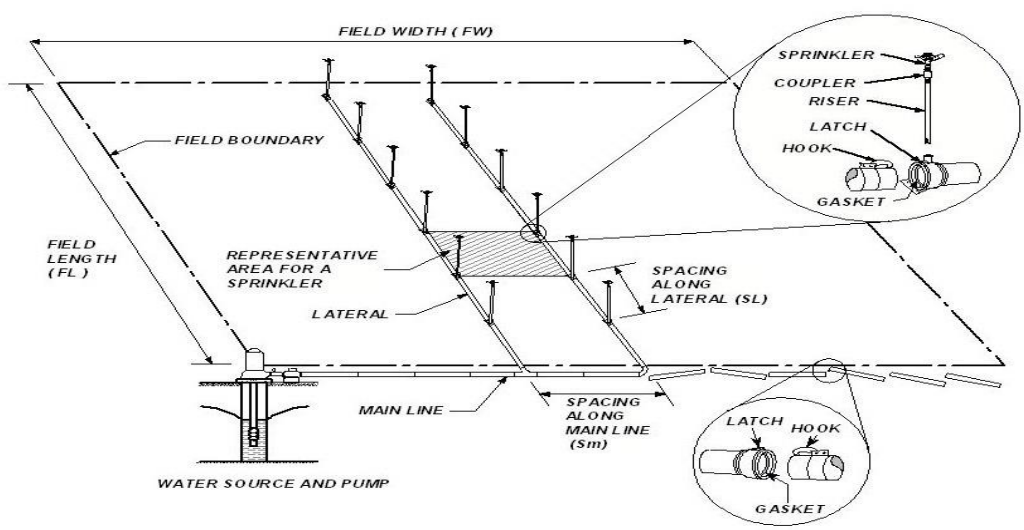

Figure 1. Layout and system components of a set sprinkler system (Martin et al., 2007a)

Whenever possible laterals should be oriented perpendicular to the prevailing wind direction, hence larger lateral spacing (and reduced number of laterals) can be used to cover the irrigated field. The spacing between the laterals along the mainline and the spacing between sprinklers along the laterals are set such that the wetted area around adjacent sprinklers is adequately overlapped to produce satisfactory level of uniformity. The required overlap depends on sprinkler characteristics, wind speed and direction, and required level of uniformity.

2.2.2 System components (Mainline, laterals, sprinklers)

In solid-set sprinkler systems, the mainline is a pipe set in place permanently or at least for the irrigation season. It has a regularly spaced outlet with valves to control the flow into each lateral. Typically, the laterals are of aluminum tubing and are in sufficient number to cover the entire irrigated field. They are fitted with sprinkler riser pipes set at regular distances on which individual sprinklers are mounted (Figure 1). A solid set system uses low to medium capacity sprinklers spaced between 30ft-80ft (9.1m-24.4m) apart (Keller and Bliesner, 1990, Martin et al., 2007a). As the irrigation stream passes through a sprinkler nozzle, the pressure is fully converted to velocity head spraying irrigation water over a wetted diameter that varies as a function of the pressure head at the nozzle and sprinkler design factors (sprinkler type, nozzle size, and stream trajectory angle).

A number of factors affect the selection of a sprinkler for a particular application: sprinkler design (type of sprinkler, nozzle size, stream trajectory angle, design pressure and associated discharge and wetted diameter), type of crop, and weather (mainly wind speed) as related to uniformity of application. In general, the most economical sprinkler system is one that uses a sprinkler with the lowest discharge (considering application rate requirements) at the widest practical spacing (Keller and Bliesner, 1990). At system design stage it is generally assumed that if the sprinkler is operated at manufacturer specified design pressure in a relatively low wind speed condition, it produces a distribution pattern (around the sprinkler), when adequately overlapped results in an overall uniformity that equals or exceeds the desired level of uniformity. Manufacturers catalogue provides sprinkler specification (nozzle size, shape, stream trajectory angle, material) and performance data (wetted diameter and discharge as a function of pressure) based on tests under specific set of conditions (often no wind condition and a given riser height), which can be used for design purposes. Sprinkler discharge, q_s *(L/s)*, is important criteria in sprinkler selection and an initial estimate of q_s can be obtained from

$$q_s = \frac{S_L S_m I}{3600} \quad (1)$$

where S_L = sprinkler spacing along the lateral *(m)*, S_m = lateral spacing along the main *(m)*, and I = required average application rate *(mm/h)*, which is a function of gross application depth, d_g *(mm)*, duration of irrigation application, T_i *(h)*, and soil intake characteristics, and can be expressed as

$$I = \frac{d_g}{T_i} \quad (2)$$

It is recommended to keep the application rate lower than the steady state intake rate of the soil to prevent surface runoff. Recommended sprinkler and lateral spacing are typically expressed in the literature as fractions of the sprinkler wetted diameter as a function of wind speed. Given a sprinkler layout and the required application rate, sprinklers that closely match the requirements of discharge and wetted diameter with the minimum operating pressure can be selected from manufacturer's catalogue.

Because of wind effects and variations in pressure distribution within the sprinkler system, actual performance of a sprinkler under field conditions may differ from manufacturer data. Manufacturer's catalogue can be used as starting point in sprinkler selection during system design. However, evaluation of sprinklers under typical operating conditions can be done to determine actual performance. Both one-sprinkler and overlapped sprinkler tests can be used to evaluate sprinkler performance on-site. One sprinkler tests can be conducted to ascertain the sprinkler characteristics (wetted diameter and water distribution pattern under a sprinkler) under actual operating conditions and overlapped sprinkler tests are needed to evaluate irrigation application uniformity under field conditions.

Sprinkler performance data collected through field tests are more realistic. However, inexpensive and a more exhaustive evaluation of sprinkler irrigation performance can be conducted with mathematical models. In which case, data generated through limited field studies would be used for model calibration and evaluation. Mathematical models can then be used to simulate the spatial distribution patterns of precipitation about a sprinkler, taking into account wind speed and direction, sprinkler design factors, and nozzle pressure (Martin et al., 2007a; Playan et al., 2009). The simulation results for a single sprinkler can be combined to determine the distribution pattern under a set of overlapped sprinklers. In this study, sprinkler characteristics will be obtained from manufacturer's catalogue.

Considering a rectangular field typical of the Yuma Valley, given a sprinkler specification and system layout; an initial estimate of the required system discharge, Q_s *(L/s)*, can then be computed as the product of the sprinkler discharge, q_s, and the number of sprinklers along the lateral, N_L, and number of laterals along the mainline, N_m:

$$Q_s = q_s N_L N_m \qquad (3)$$

Data relating system discharge with total system head can be used to select a pump that that can provide the required system discharge and head at the highest efficiency.

2.2.3 Water source and pump

For field-scale sprinkler irrigation systems, typically, the requirement is to deliver water at relatively high discharges with relatively low heads, hence centrifugal pumps are the most widely used types of pumps for such applications (Duke, 2007). In cases where larger head is needed, turbine pumps (multilevel centrifugal pumps) are used. The pump characteristics must be such that it provides the required sprinkler system discharge and head, while operating at or close to maximum efficiency. Depending on cost and convenience, the drive unit can be an electric motor or an internal combustion engine. Matching the drive unit with the pump is an important design consideration. The pump and the drive unit are typically located near the water source. Irrigation water can be obtained from a surface source such as a canal or a reservoir or from a subsurface source such as a well. For field-scale systems the most preferred location of the water source is somewhere close to center of the irrigated field as that will minimize pumping cost. However, where existing field supply canals are used as the source of water, as is the case in the Yuma Valley, there may be limited flexibility in locating the water source.

2.3. Basic pipeline hydraulics, a review

The hydraulics of a field-scale agricultural sprinkler system is a physical description of water flow through an open pipeline network, consisting of a main, possibly submains, and laterals, each with multiple outlets. Outlet discharges vary, however, discharge within a segment of a lateral or a mainline in between outlets is constant and obeys the same general physical principles as the hydraulics of a flow-through pipe with constant discharge. At the scale of an irrigated field transient flow typically occurs over short durations following valve opening or closure (e.g., when a pump is turned on or off). Hence, during normal operations flow in such systems can be hydraulically described as steady without loss of generality. This implies that simpler forms of the energy conservation and mass continuity equations (applicable to steady incompressible flow) can be used to describe the hydraulics of such systems (Granger, 1995; Larock et al., 2000; Miller, 2009). In subsequent discussion, the basic hydraulic principles/concepts, associated equations for computing friction and local head losses, and the distribution of the components of the specific energy along the length of a flow-through pipe (a pipe without outlets) are discussed first. The results will then be generalized for pipes with regularly spaced outlets along their lengths, such as sprinkler laterals and mains.

2.3.1. Flow in a flow-through pipe segment

Hydraulics of a flow-through pipe (Figure 2) can be described based on the principles of energy and mass conservation. The components of total specific mechanical energy at any given point along a pipeline consist of: elevation from reference datum to the center line of pipe, z, the pressure head, h, and the kinetic energy (velocity head, $V^2/2g$). The energy equation for one dimensional steady incompressible flow written between any two sections along the pipe, e.g., sections *1* and *2* (Figure 2), states that the specific mechanical energy at section *1* should be equal to the algebraic sum of the specific mechanical energy at section *2*, and the friction and local head losses between sections *1* and *2*:

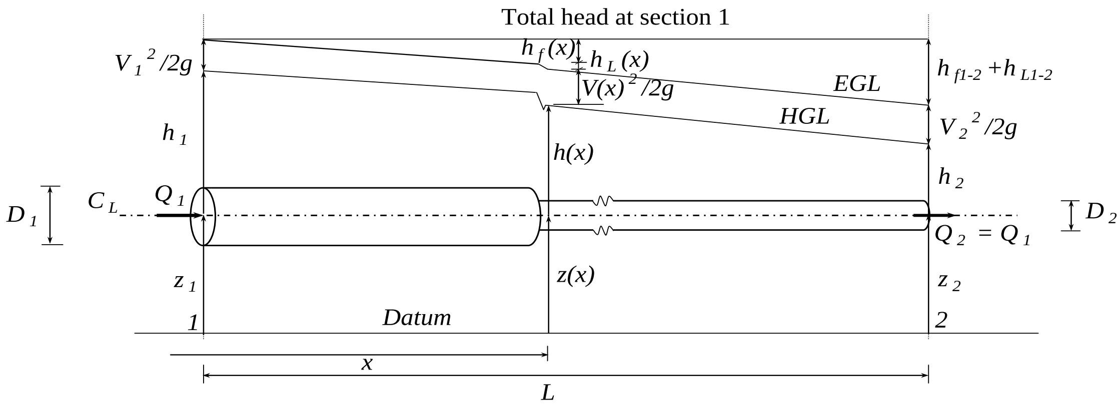

Figure 2 Components of specific energy and energy loss in a pipe without outlets: *D* = inside diameter of pipe *(m)*; C_L = center line of pipe, *Q* = discharge, *L/s; EGL* = energy grade line *(m); HGL* = hydraulic grade line *(m); z* = elevation of center line from datum *(m); h* = pressure head *(m); V* = average cross-sectional velocity, *L/T;* h_f = friction head loss *(m);* h_L = local head loss *(m);* *x* = distance from inlet end *(m);* and *L* = distance between sections 1 and 2 *(m)*

$$z_1 + h_1 + \frac{V_1^2}{2g} = z_2 + h_2 + \frac{V_2^2}{2g} + h_{f\,1-2} + h_{L1-2} \qquad (4)$$

If energy is added to the fluid in between sections 1 and 2 by a mechanical device such as a pump, it can be taken into account by adding or subtracting it to the left hand side or the right side of Eq. 4, respectively. For steady flow condition, the continuity equation reduces to:

$$Q_1 = Q_2 \qquad (5)$$

Although a third equation can be obtained from the application of the principle of momentum conservation, this equation is not used in the hydraulic design or evaluation of field-scale sprinkler pipe networks. It is often invoked in such applications as the design of structural elements of a pumping station and of a mainline supplying water to large scale irrigation systems, or a version of it is used in the physics based description of the distribution of irrigation stream ejecting from sprinklers. These topics are outside the scope of this study, hence the momentum equation is not presented here. In Eqs. 4 and 5, the elevation, *z*, pressure head, *h*, and discharge, *Q*, and the mechanical energy input, if any, can be determined through measurements. The friction and local head losses can be computed with appropriate equations.

Equations for computing friction head loss

The Darcy-Weisbach and the Hazen-Williams equations are commonly used to compute friction head loss, h_f *(m)*, in sprinkler hydraulic applications (Martin et al., 2007b; Keller and Bliesner, 1990). The Darcy-Weisbach equation (the most theoretically sound equation for h_f) is given as:

$$h_f = k_{dw} f \frac{Q^2}{D^5} L \qquad (6)$$

where k_{dw} = a dimensional constant equal to $10^{7.917}$ mm^5s^2/L^2, L = pipe length *(m)*, Q = discharge through the pipe section *(L/s)*, D = pipe diameter *(mm)*, and f = a dimensionless friction factor, which is a function of the surface roughness characteristics of the pipe material and the Reynolds number, *Re* (-), a dimensionless number used as a measure of the relative strengths of the inertial and viscous forces in the flow field:

$$R_e = \frac{VD\rho}{\mu} = \frac{4Q\rho}{\pi D\mu} \qquad (7)$$

In Eq. 7, μ = dynamic viscosity of water *[Kg/(ms)]* which is a function of the temperature of the flowing water and ρ = mass density of water *(Kg/m³)*. Given a pipe material and diameter, the relative roughness (defined as the ratio of the absolute roughness to pipe inside diameter, *e/D)* is used as a measure of the effect of pipe surface roughness on the friction factor, *f*, Eq. 6 (Larock et al., 2000; Keller and Bliesner, 1990). The relationship *f(Re,e/D)* is summarized in a logarithmic scale graph, the Moody diagram, Figure 3. The Moody diagram has four regions: the laminar, the critical, turbulent transition, and fully turbulent rough. For low velocity flows, where viscous forces are dominant (*Re<2000*, laminar flow) energy loss is entirely due to internal (viscous) friction and the friction factor *f* is a function of *Re* described by:

$$f = \frac{64}{Re} \qquad (8)$$

When flow velocity increases to an extent that *Re* exceeds *4000* (turbulent transition zone, Figure 3), the friction factor, *f*, becomes a function of both the Reynolds number and the relative roughness. The turbulent transition zone (Figure 3) is bounded by the dashed line at the top and the curve for smooth pipes at the bottom. In this zone, *f* is computed with the Colebrook-White equation, Eq. 9.

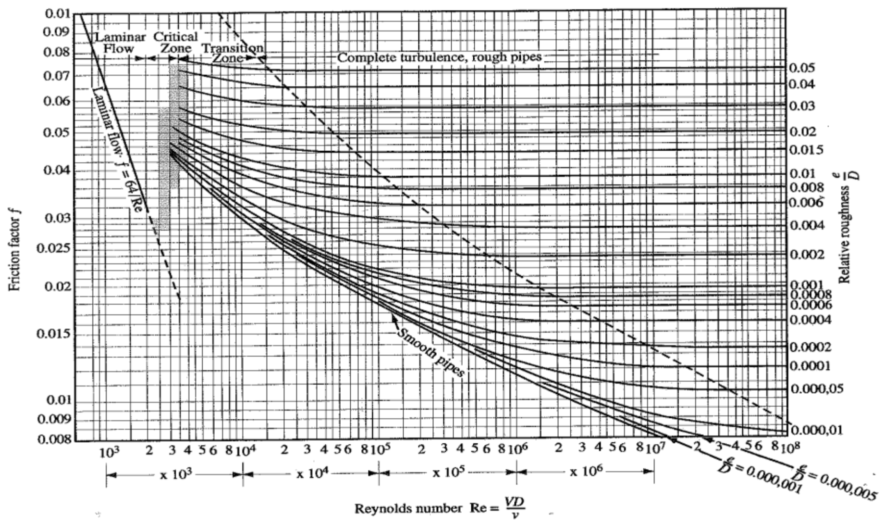

Figure 3. Friction factor for pipe flow (Moody diagram)

$$\frac{1}{\sqrt{f}} = 1.14 - 2\,log\left(\frac{e}{D} + \frac{9.35}{Re\sqrt{f}}\right) \qquad (9)$$

With a further increase in the Reynolds number beyond a threshold that varies as a function of the relative roughness, shown by the dashed line in Figure 3; the flow is in the fully turbulent–rough zone. In this zone, the friction factor, *f*, is a function of the relative roughness, *e/D*, only (Figure 3). Hence, Eq. 9 simplifies to

$$\frac{1}{\sqrt{f}} = 1.14 - 2\,log\left(\frac{e}{D}\right) \qquad (10)$$

For smooth pipes such as plastic with zero relative roughness, which represents the lower limit of the turbulent transition zone (Figure 3), Eq. 9 simplifies to

$$\frac{1}{\sqrt{f}} = 2\,log\left(Re\sqrt{f}\right) - 0.8 \qquad (11)$$

Although the Darcy-Weisbach equation is the most physically sound equation for computing friction head loss in pipe flow, computationally it can be cumbersome. Hence simpler empirical equations are often used in practice. The Hazen-Williams equation is widely used in sprinkler system hydraulics.

$$h_f = \frac{k_{hw}}{D^{4.87}}\left(\frac{Q}{C}\right)^{1.852} L \qquad (12)$$

where k_{hw} = dimensional constant equivalent to $1.22 \times 10^{10} mm^{4.87} s^{1.852}/L^{1.852}$ and C = Hazen-Williams friction coefficient (-). Equation 12 was developed based on a study in pipes larger than *75mm* diameter and discharges exceeding *3.2L/s* with *Re* greater than 5×10^4 (Keller and Bliesner, 1990). The friction factor, C, can be obtained from literature (e.g., Keller and Bliesner, 1990) for different pipe materials. It has been shown that, in addition to the relative roughness (function of pipe material), C can vary with the Reynolds number and pipe diameter. However, in practice these factors are considered limiting mainly when the equation is used in small diameter smooth plastic pipes such as those used in drip irrigation.

Equations for computing local head losses

Local head losses occur in pipe transitions, such as pipe contractions or expansions, fittings, tees, elbows, valves, where the flow is disrupted and turbulent eddies are generated and dissipated, in the process converting part of the mechanical energy to other forms of energy including heat. In general, local head losses are computed as a product of a local head loss coefficient, k_L, and the local velocity head:

$$h_L = k_L k_{vh}\left(\frac{Q_1}{D_1^{\ 2}}\right)^2 \qquad (13)$$

In Eq. 13, k_{vh} = dimensional constant of the velocity head term, equivalent to $10^{4.917} mm^4 m(s/L)^2$, Q_1 = discharge just upstream of the flow disruption *(L/s)*, and D_1 = upstream pipe diameter *(mm)*. If local head losses associated with reduction in pipe size, the velocity head typically used is the one in the downstream pipes section. For changes in pipe diameters (pipe size reduction or increase), the local head loss coefficient is a function of the ratio of the upstream and downstream cross-sectional areas only. For other kinds of pipe transitions, given the type and geometry, local head loss coefficients in theory can vary as a function of the local Reynolds number, inflow and outflow conditions, and surface roughness (Miller, 2009). However, accurate determination of the effects of these factors for sprinkler system modeling applications is often impractical, hence they are typically treated as constant parameters that depend on the type and geometry of the pipe transition. They can be obtained from manufacturer's catalogue or from literature sources (e.g., Keller and Bliesner, 1990; Granger, 1995) or in principle can be determined through measurements.

2.3.2 Sprinkler lateral and main

A sprinkler lateral or a mainline is a special type of manifold, a pipe consisting of multiple outlets with spacing, diameter, and discharge that are constant or variable over distance. For solid set sprinkler systems spacing between outlets along a lateral or a mainline are constant and discharges are typically variable. Figure 4 depicts a schematic of the distribution of the components of the total specific energy along a pipe segment with constant diameter and equally spaced multiple outlets (a sprinkler lateral or main). Over the entire length of a lateral or a mainline, flow velocity is spatially variable, however, in between outlets (considering a constant pipe size) flow can be considered uniform. In relatively simple and small field-scale sprinkler systems that are of concern here, transient flow occurs over short durations following valve opening or closure (e.g., when a pump is turned on or off). Hence, considerations of transient flow conditions are important only for the design of structural elements of the system, if any, and determination of pressure ratings of pipes. In general, during normal operations, flow in such systems can hydraulically be described as steady flow and Eqs. 4 and 5 are applicable. There are theoretical limitations to the application of the energy equation (Eq. 4) across a node, where flow is divided into a fraction flowing into a sprinkler riser pipe and the through-flow along the lateral, because of the nonuniform kinetic energy distribution over a pipe cross-section (Larock, et al., 2000; Graber, 2010). However, for most practical applications these limitations are considered negligible. Hence, the energy equation, Eq. 4, in combination with the continuity equation, is often used to describe

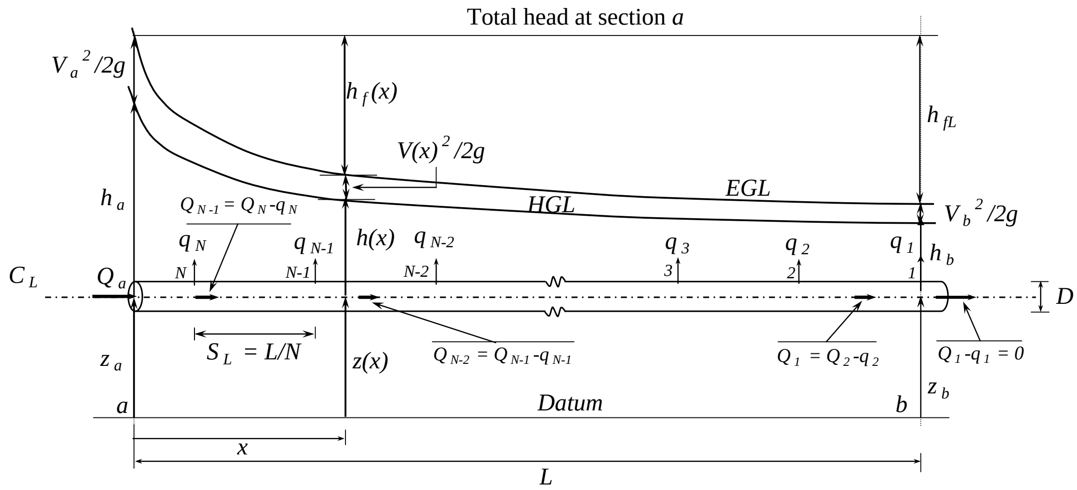

Figure 4. Components of specific energy along a sprinkler lateral (*Q* = discharge through pipe (lateral or mainline), *q* = outlet discharge, S_L = spacing between outlets, *N* = number of outlets, and *L* = pipe length. Note that outlets are numbered starting from the distal outlet following the same sequence as the computation of pressure and outlet discharge distribution)

flow across such a node. As can be noted from Figure 4, the continuity equation for such a node can then be stated as: the algebraic sum of discharges flowing into and out of a node, Q_i, must be add up to zero:

$$\sum Q_i = 0 \qquad (14)$$

Considering sprinkler laterals as manifolds, a rigorous and flexible formulation of the sprinkler lateral hydraulic problem can be obtained by coupling the energy equation for each lateral segment with the continuity equation at a node. The resulting set of equations can then be solved iteratively starting from the distal end sprinkler and moving sequentially upstream along the lateral (e.g., Larock et al., 2000; Miller, 2009).

A numerical procedure analogous to this approach was proposed for sprinkler laterals by Hathoot et al. (1994). In contrast to the standard procedure used in manifold hydraulics, with this approach calculation begins at the inlet end of the lateral with an assumed total head there and proceeds downstream. To the extent that the total head at the lateral inlet cannot be defined with any degree of certainty a priori, the procedure can be computationally less efficient compared to the standard method, referred above.

Hydraulically speaking, sprinkler mains can also be considered as manifolds consisting of multiple pipe sections and outlets (lateral inlets) with known hydraulic characteristics (e.g., Kang and Nishiyama, 1995). In which case the same numerical approach as the one described for laterals can be used to compute the distribution of discharge, pressure head, and total head along the main as well, given the hydraulic characteristics of its outlets.

Because of limitations in computational resources, in the past analytical formulations derived based on a set of simplifying assumptions were commonly used in sprinkler hydraulics. Christiansen (1942) approximated the friction head loss in a sprinkler lateral as the product of the friction head loss in an equivalent flow through pipe (computed with a suitable friction head loss equation) and a friction reduction factor. Christiansen's friction reduction factor was derived assuming (Heermann and Kohl, 1980; Keller and Bliesner, 1990; Martin et al., 2007b): the first outlet is placed at a distance of a full sprinkler spacing from the lateral inlet, the lateral has equally spaced outlets, outlet discharges are spatially invariant, lateral diameter, slope, and hydraulic resistance coefficient are all constant, and no outflow at the downstream end. Subsequent modifications have allowed for increased flexibility in terms of the location of the first sprinkler with respect to the lateral inlet (Jensen and Fartini, 1957; Anwar, 1999) and in terms of provisions for computing friction head losses in tapered laterals (e.g., Keller and Bliesner, 1990; Anwar, 1999; and Yitayew, 2009) and in laterals with residual outflow discharge at the downstream end (Anwar, 1999). Nonetheless, most of the limitations of the classic approach (Christiansen, 1942) remain. Vallesquino and Escamilla (2002) presented a computational procedure for approximating the spatial variation of sprinkler discharges along a lateral. The procedure involves step-wise refinement of initial results, computed with the classic approach, through power-series approximations. The method has also the flexibilities of some of the approaches described above and it can also account for variations in lateral slope and outlet spacing.

The basic approach described above and the assumptions it is based on are generally valid for most practical sprinkler system applications. However, some of these assumptions are too restrictive to be applied to diverse system topologies, such as those with nonuniform slope and outlet spacing as well as flow conditions in which velocity head and local head losses cannot be considered negligible. The limitation of the approach described above could become readily evident when considering the solution of a hydraulic problem involving a long relatively small diameter lateral with a highly nonuniform specific energy, and hence sprinkler pressure head and discharge, distribution. Current advances in computing allow the implementation of the more rigorous approach in sprinkler system hydraulic characterization, design, and evaluation applications.

2.3.3 Hydraulic design considerations

In sprinkler systems, uniform application of irrigation water is a prerequisite to attain adequate and efficient irrigation. However, because of sprinkler pressure head variation over the irrigated field, as a result of energy loss and possibly topographic effects, sprinkler discharges are spatially variable (see discussion on basic pipe line hydraulics in section 2.3). In farms where surface irrigated fields are converted into pressurized systems, such as those of the Yuma Valley Irrigation District, typically the land surface is level or nearly level. In these farms the effect of topography on pressure distribution over the sprinkler system network is typically lower than that of energy loss. Considering that pipe diameter has the most significant effect on the amount of friction head loss (and hence on the sprinkler application uniformity) as well as on system cost, it constitutes a key sprinkler system design variable. Assuming all other factors remain the same, larger diameter laterals imply higher irrigation uniformities, but also require higher capital expenditures. On the other hand, smaller pipe sizes result in lower uniformities and higher running costs, but entail lower capital expenditures. Therefore, an important goal in sprinkler system design is the selection of lateral and mainline diameters that balances the conflicting needs of uniformity and system cost.

In theory, the sprinkler system design problem can be formulated in the context of economic cost/benefit optimization (e.g., Holzapfel et al., 1990). However, because of limitations in data availability and to some extent problem complexity irrigation performance based design criteria coupled with hydraulic analysis is typically used to derive satisfactory designs. The acceptable range of sprinkler pressure (hence sprinkler discharge) variation along the lateral can be set by the engineer as a function of the desired level of uniformity. A rule-of-thumb (considered to provide a balance between irrigation uniformity and economic cost) widely used in sprinkler lateral design is that the sprinkler pressure head variation along a lateral should not exceed 20% of the average sprinkler pressure head, which is equivalent to about 10% variation in sprinkler discharge along the lateral (Keller and Bliesner, 1990). Maximum velocity head should also be considered, especially if the computational approach used assumes velocity head to be negligible. The same set of design criteria can be used as a guideline in mainline design as well.

2.3.4 System hydraulic characteristics

Given a sprinkler system (layout, sprinkler specification, pipe sizes, location and type of pipe appurtenances, and friction and local head loss coefficients), for each system discharge, Q_s, the corresponding total dynamic head, H_s, can be computed as the sum of the static and the dynamic head of the system. The type of pumps widely used in sprinkler irrigation systems are centrifugal pumps. The hydraulic characteristics and performance of such a pump is summarized in a pump characteristics curve provided by manufacturers, containing such data as: total head-discharge function, pump efficiency, and the required net positive suction head (Cuenca, 1989; Keller and Bliesner, 1990; Duke, 2007). The sprinkler system hydraulic characteristics (i.e., the functional relationship between the total dynamic head and the system discharge, H_s -Q_s) can then be superimposed on a pump characteristics curve to select the pump that can provide the required discharge and total head at maximum efficiency, while satisfying the requirements of net positive suction head. Although system characteristics curves were generated for alternative scenarios during the simulation studies, pump selection or evaluation is outside the scope of the current study.

Chapter 3. Sprinkler irrigation system for season long vegetable production in the Yuma Valley Irrigation District

3.1. System description

In decades past, solid-set sprinkler systems have been used in the Yuma Valley Irrigation District primarily to maintain favorable soil temperature and soil water status for crop germination in the first weeks of the vegetable growing season. Recently, however, the use of sprinkler systems for season long vegetable production is expanding, mainly with the view of increasing water use efficiency. A typical field-scale sprinkler system in the Yuma Valley consists of an open pipeline network to convey and distribute irrigation water over the irrigated field (e.g., Figure 1). The system components are a water source, a pump, a mainline to convey irrigation water from the source across the irrigated field and distribute it among a series of laterals that run, typically, perpendicular to the mainline itself. In general, the pumping unit, the main, and laterals all remain stationary in a set position during an irrigation season, although some minor relocation of laterals within the field are possible to accommodate midseason cultural practices. Flow into individual laterals is controlled by valves. These valves provide operational flexibility in terms of the fraction of the total area to be irrigated at any one irrigation event.

Sprinkler mounted riser pipes are placed at regular intervals along each lateral. The low-capacity sprinklers typically used in these systems are also better suited to irrigate the leafy vegetables grown in the area in terms of minimizing crop damage. Solid set systems are also well suited to applying light, but frequent irrigations required by these crops. Considering the relatively heavy soils of the Yuma Valley (with soil texture varying in the range silt loam to silt clay), the use of solid set systems in stead of periodic move or continuous move systems is preferable to prevent alteration of infiltration characteristics of the soil because of compaction. Although solid set sprinkler systems require relatively larger capital expenditure, they have minimal labor costs, and are amenable to automation.

3.2. System layout, water source, pump, and drive unit

In the Yuma Valley Irrigation District the land surface is typically flat and precision leveling is often performed prior to every cropping season, hence topography is not a significant factor in terms of system layout selection. Because the soils in the Yuma Valley are relatively heavy and the water table is shallow, crops are grown on furrow beds to improve subsurface drainage and maintain a root zone soil water status favorable for crop growth. In farms where sprinkler systems are practiced only during the first few weeks of the cropping season as supplementary irrigation and for environmental control purposes, the layout of the sprinkler system is dictated by the layout of the surface irrigation system, which is the primary irrigation system. In which case, the laterals are installed along the furrows and the mainline runs parallel to the field supply canal. On the other hand, in farms where sprinkler systems are used for season long production, the geometry of the field appears to be the primary factor in determining the sprinkler system layout. Typically, furrows, hence laterals, are installed parallel to the longest dimension of the field, which could also be parallel to the field supply canal. In which case, the mainline runs perpendicular to the field supply canal. Such a layout is convenient and economical for farm machinery operations.

There are two types of field-scale solid set sprinkler system layout configurations that are widely used in the Yuma Valley Irrigation District. The most commonly used field layout configuration is one in which the mainline is installed across the head end of the irrigated field supplying irrigation water to a line of laterals (Figure 5a). Such a system is described here as having a single-line laterals layout configuration. Another field sprinkler system layout configuration widely used in the area consists of a mainline supplying irrigation water to two sets of laterals, each installed on either side of the main (Figure 5b). Such a system is referred here as having a double-line laterals layout configuration. The mainline of a system with double-line laterals layout configuration is installed in between two adjacent irrigated fields or somewhere within a field and has multiple water off-take nodes, each supplying water to a pair of laterals set on either side of the main (Figure 5b). With this layout configuration each set of laterals irrigate either some fraction of the field or one of the adjacent fields, as the case may be. Typically, the water source for a field-scale solid set sprinkler system in the Yuma Valley is an open canal. Given that the requirement is to pump relatively large discharges at low heads, the type of pumps that are commonly used are centrifugal pumps. The drive units for these pumps are often internal combustion engines.

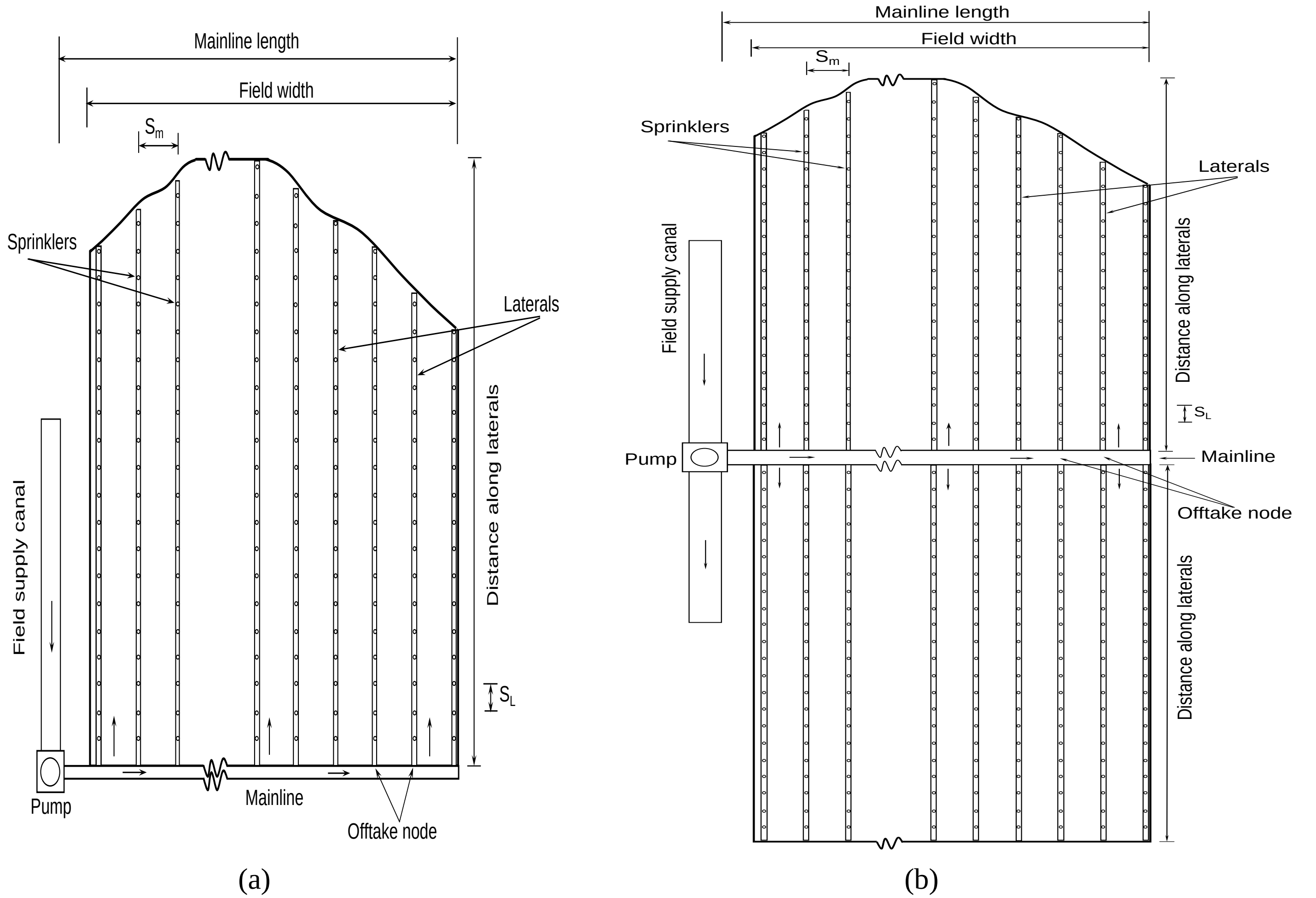

Figure 5 Field-scale solid set sprinkler system layout configurations (a) single-line laterals (b) double-line laterals (S_L = sprinkler spacing along laterals and S_m = lateral spacing)

Chapter 4. Methodology

4.1 Introduction

Field evaluations were conducted to estimate sprinkler irrigation uniformity levels under current irrigation management practices in growers’ fields in the Yuma Valley Irrigation District. Additional field evaluations were conducted in the Maricopa Agricultural Center of the University of Arizona as well. During each field evaluation plot scale irrigation uniformity tests (involving rain gages arranged in rectangular grids) were conducted. Such tests are replicated over the irrigated field, based on which the plot scale irrigation uniformity estimates are scaled-up to field-wide uniformity. During each of the field evaluations, conducted at the Maricopa Agricultural Center, hydraulic data (consisting of pressure head and discharge measurements) were collected along the laterals covering much of the irrigated field. These data sets were used in the evaluation of the field-scale sprinkler system hydraulic model developed as part of the current study.

A mathematical model with a capability to conduct field-scale hydraulic simulation and design of a solid set sprinkler irrigation network with single-line laterals layout configuration was developed and evaluated with field data as part of an earlier study (Zerihun et al., 2011; Zerihun and Sanchez, 2011). Within the framework of the current study, the model has undergone further developments to provide it with hydraulic simulation and design functionalities for sprinkler systems with double-line laterals layout configuration. Furthermore, numerical modules were developed and incorporated into the new version of the model, enhancing the mathematical rigor of the model (section 4.4). The current version of the model also has the capability to compute test-plot scale and field-scale irrigation uniformity based on field data.

4.2 Description of study site and sprinkler system

Yuma experiment: Two irrigation evaluations were conducted in growers’ fields in the Yuma Valley Irrigation District in the winter season of 2012. The soils of the evaluation farms can be described as silty clay loam. The field sprinkler systems used in these evaluations have single-line laterals layout configuration. One of the irrigation evaluations were conducted in a sprinkler system consisting of 14 laterals set at a regular spacing of 35.0ft. Each lateral is 1290.0ft long and has 43 sprinklers installed at a spacing of 30.0ft. The mainline is 595.0ft long, with the upstream most lateral set at 140.0ft distance form the system inlet. Hence, the effective irrigated area of the farm is 14.7acre. The second field-scale sprinkler system used in the study, consists of 36 laterals installed along a mainline of 1244.0ft length. However, the field evaluation covers only the upper 609.0ft long section of the mainline, in which 18 laterals are installed at a regular spacing of 35.0ft (with the first lateral set at a distance of 14.0ft from the mainline inlet). Each lateral is 1530.0ft long and has 51 sprinklers set at a regular spacing of 30.0ft. The area of the field covered by the irrigation evaluation is 21.6acers.

Maricopa experiment: Additional irrigation evaluations were conducted in a sprinkler irrigated field in the research farm of the Maricopa Agricultural Center of the University of Arizona in the summer of 2012. The main objective of this study is to conduct hydraulic evaluations of a field-scale sprinkler system with double-line laterals layout configuration. However, along side the hydraulic measurements, irrigation uniformity evaluations were also conducted. The soils of the test farm can be characterized as loam. As shown in Figure 6, the sprinkler system used in this study has a double-line laterals layout configuration. The irrigated field has a rectangular shape and it is 210.0ft wide and 1260.2ft long, covering an area of 6.15acre. The water source is a lined field supply canal running along the edge of the field and water was pumped (with a centrifugal pump) from the canal into a mainline. The mainline runs across the shortest dimension of the field, dividing the field into two equal halves of each 210.0ft width and 630.0ft (Figure 6). The mainline, which spans the width of the field (210.0ft), is comprised of 152.4mm diameter aluminum pipe sections with six water off-take nodes, each supplying water to a pair of laterals running perpendicular to the main. The upstream end off-take node is set at 10.0ft from the pump and the remaining five off-take nodes were set at an equal distance of 40.0ft. Each lateral consists of 630.0ft long aluminum pipe with a constant diameter of 76.2mm and has twenty-one sprinklers set at a regular spacing of 9.14m. The sprinklers used in this study are a mix of Rain Bird 14J model (a predecessor of the Rain Bird 14VH model), nozzle size 7/64″ and WeatherTec 10-20 model with a nozzle size 7/64″. The head discharge characteristics of these two types of sprinklers is essentially the same with a maximum error of less than 0.5%. Hence, in subsequent analysis WeatherTec 10-20 sprinkler with nozzle size of 7/64″ (*WeatherTec Corporation: http://www.weathertec.com*) is used.

Topographic survey was conducted covering the entire field with a bench mark set at an elevation of 328.08ft (100.0m) from an assumed datum. Based on which the

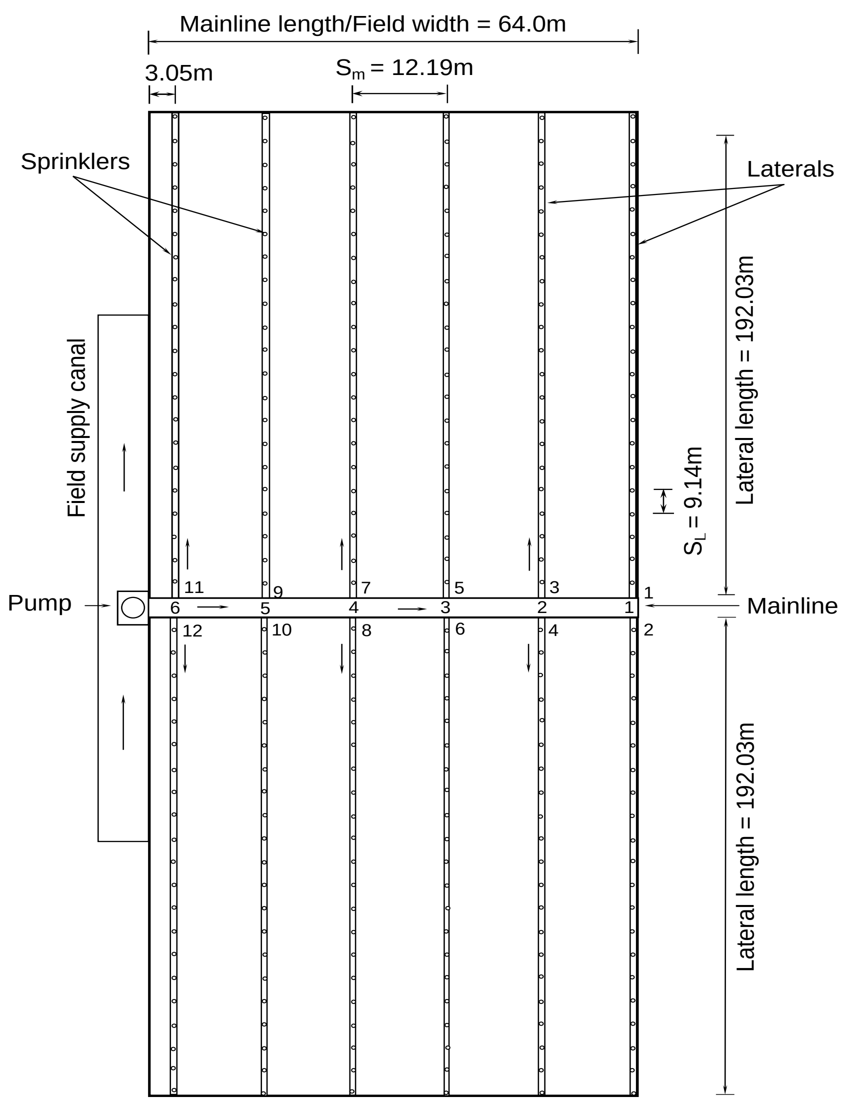

Figure 6 Layout of the sprinkler system used in the field study in the Maricopa Agricultural Center the University of Arizona

average longitudinal slope (slope along the longest dimension of the field) is computed as 0.01% and the cross-slope (slope along the shortest field-dimension) is determined to be 0.03%. Note that topography of the field is such that the even-numbered laterals run up the slope, hence they have a 0.01% slope and the odd-numbered laterals have a -0.01% slope (Figure 6). The mainline runs down slope, hence has a -0.03% slope.

4.3 Field evaluation of irrigation application uniformity

4.3.1 Introduction

Typically field evaluation of a solid set sprinkler irrigation uniformity is conducted over a rectangular test-plot, covering an area circumscribed by four adjacent sprinklers, with dimensions equal to the sprinkler spacing (along laterals) and the lateral spacing (Figure 7). The test-plot is further discretized into smaller grid squares and at the center of each grid-square or in some cases at the grid points a rain gage is placed. Data collected through such tests can be used to characterize irrigation uniformity at the scale of a test-plot. Typically, sprinkler pressure head (and hence discharge) vary through the field. In addition, sprinkler characteristics can vary through the field due to nonuniform wear and tear and/or inadvertent mixing of sprinklers with different hydraulic characteristics. Hence, test plot-scale irrigation performance estimates can be appreciably different from the field-scale performance. In order to take into account the effects of these variations on field-scale irrigation application rate and uniformity, similar tests need to be conducted in more than one test-plots over the irrigated field. In theory the most accurate field-scale evaluation may require conducting distribution uniformity tests covering the entire irrigated field, however, such an approach is impractical. An approximation of a field-scale performance estimate can be obtained, with reduced cost and effort, based on a relatively small number of plot scale tests distributed over the field.

The effect of system hydraulics on irrigation uniformity in a field-scale solid set sprinkler system is predictable. Considering a nearly flat field surface (common in the study area) and spatially invariant laterals/mainline diameters and sprinkler characteristics (common attributes for sprinkler systems in the Yuma Valley); the spatial variation of sprinkler pressure head (and hence discharge) can be shown to be a decreasing nonlinear convex function of distance from the system inlet. This suggests that in order to sample the effects of sprinkler pressure head variability on field-scale irrigation uniformity effectively, the spatial distribution of the test-plots may need to be skewed toward the inlet of the sprinkler system.

A field study based on such a design was conducted and the results showed that within a given field evaluation appreciable variations in the test-plot scale UCC *(*ranging between 0.77 and 0.85) and DU_{lq} (ranging between 0.69 and 0.77) can exist in a well maintained and operated sprinkler system (Zerihun et al., 2011b). In addition, uniformity data collected within the same field during three comparable irrigation events (considering hydraulic and ambient weather condition) also showed significant variations in test-plot scale UCC *(*ranging between 0.77 and 0.87) and DU_{lq} (varying between 0.69 and 0.82). On the other hand, hydraulic measurements and simulation results showed that sprinkler pressure head and discharge variations over the irrigated field, and its effect on irrigation uniformity, is limited (mainly due to the relatively large pipe diameters used in the sprinkler system and the nearly level land surface slope of the farm).

Overall, the preceding discussion suggests that in the test farm used in the study, the effect of spatial variations in system hydraulics could be less significant. It, nonetheless, shows that some combination of other factors that affect irrigation uniformity, including possible variations in sprinkler characteristics due to nonuniform wear and tear, inadvertent mixing of sprinklers with different hydraulic characteristics, and issues related to routine sprinkler system maintenance and installation could be significant contributing factors. The inference that stem from the preceding discussion is that in field-scale sprinkler system uniformity evaluation it is preferable to use more than one plot scale tests to be able to sample the effects of these factors on irrigation uniformity.

4.3.2. Layout of an irrigation uniformity test-plot and measurements

The layout of rain gages in the irrigation uniformity test-plots used in the Yuma Valley and Maricopa studies are depicted in Figures 7a and 7b, respectively. In the Yuma Valley study each test-plot is setup in between two adjacent laterals, and circumscribed by four sprinklers, covering a rectangular area measuring 30.0ft along the laterals (sprinkler spacing along laterals) and 35.0ft in a direction normal to the laterals. In the field study conducted in the Maricopa Agricultural Center each test-plot covers an area of 30ft (sprinkler spacing along laterals) by 40ft (spacing between laterals). The type of rain gage used in this study is a 10″ long tapered (conical) rain gage that can measure 1.0-140.0mm depth of precipitation with a measurement precision of 1.0mm. Each rain gage is mounted on a plastic stake provided by the manufacturer and is fastened to a wooden post providing it sufficient clearance from the ground (preventing splash from entering the rain gages) when installed in a test-plot. During an irrigation evaluation three test-plots distributed over the irrigated field, each representing an equal fraction of the total area of the field, were installed.

Depending on the degree of overlap between adjacent sprinklers, which varies with time in any given irrigation event, a rain gage in a test-plot receives precipitation from a number of sprinklers. Typically, the precipitation depths collected in each rain gage are recorded manually immediately following the end of a test irrigation event. However, when it is inconvenient to do so and when the time that precipitation readings were taken and the time an irrigation evaluation event ended is different, and then evaporation data from a control rain gage is used to correct the measured precipitation depths. In the Yuma Valley studies weather data (mainly wind speed) was measured with

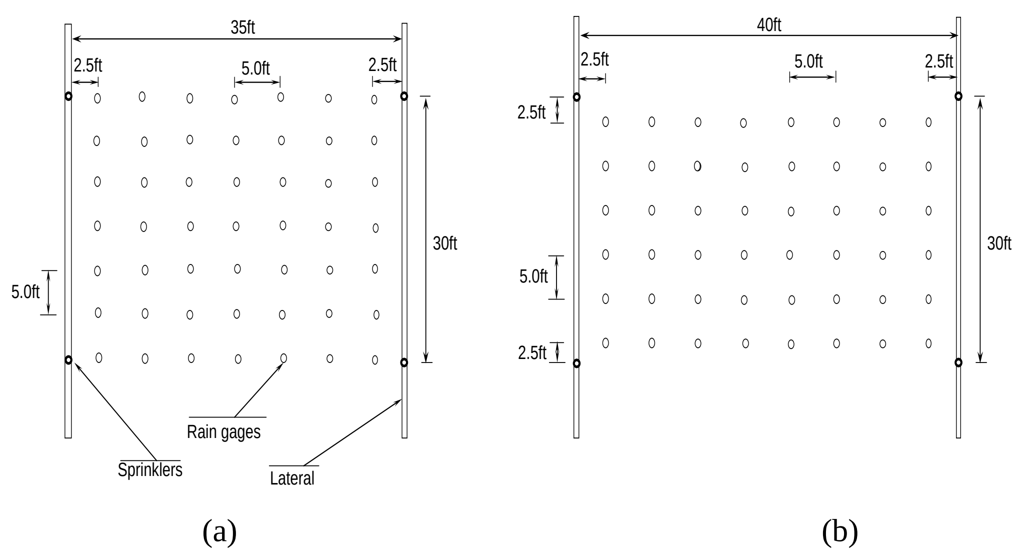

Figure 7 Layout of the irrigation uniformity test-plots used in: (a) The Yuma Valley field evaluation and (b) Maricopa Agricultural Center field evaluation

a nearby micro-meteorological station. In the Maricopa studies, weather data from a nearby AZMET (the Arizona meteorological network) station for the duration of the irrigation evaluation event was downloaded from AZMET website (*http://ag.arizona.edu/azmet/*). The data used in this study contains a record of the hourly average wind speed and direction.

4.3.3. Hydraulic (discharge and pressure head) measurements

In the field study conducted in the Maricopa Agricultural Center of the University of Arizona, hydraulic (pressure head and discharge) measurements were made along the main and laterals. The hydraulic, geometric, and topographic characteristics of the sprinkler system used in this study are described in sections 4.2 (Figure 6). The flow meter used to measure lateral discharges in the current study is a propeller meter that can measure discharges of up to 250.0GPM with a measurement precision of 10.0GPM. It also has a totalizer with a digital display. Pressure gages that can measure a maximum pressure head of 70.0m water column (100.0psi) with measurement precision of 1.4m (2.0psi) was used to measure pressure head along laterals.

Prior to each test irrigation event, five or four pressure gages were installed along selected laterals (section 5.3.1) and flow meters were installed at a point just upstream of the first sprinkler from the inlet end of each of the laterals. In addition, as described above, topographic survey was conducted in the irrigated field to determine average slopes along the mainline and the laterals. The measured pressure heads and elevations at the computational nodes along the laterals will be used to compute hydraulic grade lines. The hydraulic model will then be evaluated by comparing the simulated and measured hydraulic grade lines along the laterals and lateral inlet discharges.

4.3.4 Irrigation uniformity equations

Sprinkler field tests are used to determine application uniformity at the scale of a test-plot. In the current study, irrigation uniformity is measured with two indices:
(*1)* Christiansen's uniformity coefficient, *UCC (-)*, a good measure of spatially distributed nonuniformity, is given as

$$UCC = 1.0 - \frac{\sum_{k=1}^{K} |d_k - d_{av}|}{\sum_{k=1}^{K} d_k} \quad (15)$$

In Eq. 16, k = rain gage indices *(-)*, K = the total number of rain gages in a test-plot *(-)*, d_k = depth of water collected by individual rain gages *(mm)* and d_{av} = average depth collected over the test-plot *(mm)*, and *(2)* the low-quarter distribution uniformity, DU_{lq}*(-)*, which is a good measure of localized significant negative deviations from the average depth

$$DU_{lq} = \frac{d_{lq}}{d_{av}} \quad (16)$$

where d_{lq} = average of the lowest quarter depths *(mm)*.

In order to scale up the test-plot scale uniformity indices to field-scale, a simple averaging procedure is used. With this approach the test-plot scale uniformity (which also represents the application uniformity of the corresponding farm block) is computed with Eqs. 15 and 16. The field-scale uniformity indices are then computed as the weighted averages of the test-plot scale uniformity indices. The weighting coefficient for each test-plot is computed as the ratio of the area of the farm block that the test-plot represents to the total farm area.

4.4 Modeling study

The basic numerical algorithms used here for modeling the hydraulics of a field-scale solid set sprinkler system with single-line laterals layout configuration were developed as part of an earlier study (Zerihun and Sanchez., 2011). The modeling work performed within the frame work of the current study include: (1) The formulation and numerical solution of the hydraulic equations for a sprinkler system with double-line laterals layout configuration; (2) An interpolation scheme, based on cubic splines, was developed and incorporated into the current version of the model as an interface for coupling the numerical solutions of the lateral and mainline hydraulic equations; (3) A one-dimensional optimization algorithm is developed and incorporated into the hydraulic simulation and design functionalities of the model; (4) Enhancements were made to earlier version of the model in order to accommodate field layouts with irregular boundaries (variable lateral lengths); and (5) A new functionality for computing test-plot scale and field-scale sprinkler irrigation uniformity from field data is developed.

Overall, current version of the model is capable of conducting hydraulic characterization, design, and simulation as well as field evaluation computations at a field-scale for systems with single-line laterals or double-line laterals layout configuration. A description of the model in terms of equations and solution algorithms, available functionalities, limitations, program components and organization, and issues related to the installation and running of the program is presented in a companion document (Zerihun and Sanchez, 2012). Evaluation of the model through comparison of its output with field measured hydraulic (discharge and pressure head) data and its application in the determination of the hydraulic characteristics of the field-scale solid set sprinkler system is presented in the results and discussion section.

Chapter 5. Results and discussion

Irrigation field evaluations were conducted in farms, in the Yuma Valley Irrigation District, that grow leafy vegetables under season long sprinkler irrigation. The field study conducted in the Yuma Valley is aimed at collecting data for field-scale irrigation uniformity evaluations. Additional sprinkler irrigation field evaluations were conducted in the Maricopa Agricultural Center of the University of Arizona. The primary objective of the Maricopa study was to conduct hydraulic evaluation of a field-scale solid set sprinkler network with double-line laterals layout configuration. The hydraulic (pressure head and discharge) data collected in this study is used for evaluation of the mathematical model developed as part of the study reported here. Along side the hydraulic evaluation, irrigation uniformity evaluations were also conducted in the Maricopa field study. In subsequent sections of this chapter, measured test-plot scale precipitation data along with computed test-plot scale and field-scale application uniformity indices are presented. In addition, results of model evaluation through comparison of computed and measured hydraulic data, model based analysis of the sensitivity of field-scale sprinkler system hydraulics, and example simulations that highlight the practical applications of the model are described.

5.1 Irrigation uniformity evaluations with field data

5.1.1 Yuma Valley study

As described in the methodology section, two irrigation field evaluations were conducted in two growers' fields in the Yuma Valley Irrigation District. In each of the evaluation farms three test-plots were installed distributed over the irrigated field, each representing equal fractions of the irrigated field. As described in section 4.3, the data from test-plot measurements were used to compute plot scale irrigation application uniformity estimates (Eqs. 15 and 16). The test-plot scale estimates were then scaled up to field level through averaging. The precipitation data collected in each of the test-plots, measured wind speed, and computation of test-plot scale and field-scale irrigation uniformity along with the average precipitation depths are presented subsequently.

***Irrigation evaluation I**:* The first irrigation evaluation was conducted in a grower's field with an effective irrigated area measuring 490.0ft×1290.0ft. Irrigation duration was 7.0h. The wind speed during the irrigation evaluation vary in the range 0.0-3.7m/s with an average value of 1.8 m/s. Measured precipitation depths for each of the test-plots are summarized in Table 1. The collected depths vary from a minimum value of 7.0mm to a maximum of 81.0mm. The test-plot scale average depths vary from a minimum of 18.0mm for the middle test-plot to a maximum of 32.0mm for the upstream end test plot, with the average depth for the downstream end test-plot being 27.0mm (Table 1). Computed Christiansen's uniformity coefficient values are 0.78, 0.58, and 0.89 for the upstream end, middle, and downstream end test-plots, respectively. Distribution uniformity is 0.76 for the upstream end test-plot, 0.48 for the middle test-plot, and is 0.84 for the downstream end test-plot. The field-scale average UCC and DU_{lq} are 0.75 and 0.69, respectively. While the computed UCC and DU_{lq} for the upstream and downstream end test-plots can be considered high, the values for the middle test plot are low. In addition, it can be noted from the data for test-plot 2 (Table 1) that there is a spatial trend to the observed variation in precipitation depths within the test-plot, which is not noted in the other test-plots of the field. This suggests that factors other than wind might have been contributing to this. Perhaps some combination of such factors as sprinkler riser

Table 1 Field data and uniformity computation for irrigation evaluation I, Yuma Valley Irrigation District

			Test-plot 1							Test-plot 2							Test-plot 3						
			Number of rain gages parallel to the laterals							Number of rain gages parallel to the laterals							Number of rain gages parallel to the laterals						
			1	2	3	4	5	6	7	1	2	3	4	5	6	7	1	2	3	4	5	6	7
			Collected depth (mm)							Collected depth (mm)							Collected depth (mm)						
Number of rain gages parallel to the mainline		1	81	28	30	23	24	36	81	11	8	8	7	7	10	19	36	28	22	20	20	23	30
		2	38	28	25	25	30	30	30	10	8	8	8	8	10	13	25	24	24	30	24	25	25
		3	29	29	30	28	27	27	28	11	10	11	10	11	10	12	26	25	24	25	25	28	27
		4	30	32	33	29	25	27	28	16	15	15	15	20	15	15	27	28	28	28	29	30	30
		5	30	30	30	37	27	27	28	20	20	20	20	20	22	23	28	30	23	30	30	28	28
		6	29	28	28	26	24	25	28	34	25	23	25	23	26	30	30	30	30	25	25	27	28
		7	65	28	20	20	23	28	56	33	30	25	23	25	36	53	38	28	33	22	20	23	30
		Unit																					
Average wind speed during irrigation test		*m/s*	1.8																				
Duration of test irrigation event		*h*	7.0																				
Test-plot Scale	Test-plot size	*ft*	30.0×35.0							30.0×35.0							30.0×35.0						
	Farm block size	*ft*	430.0×490.0							430.0×490.0							430.0×490.0						
	Average depth collected	*mm*	32.0							18.0							27.0						
	UCC	-	0.78							0.58							0.89						
	DU_{lq}	-	0.76							0.48							0.84						
Field scale	Minimum depth collected	*mm*	7.0																				
	Maximum depth collected	*mm*	81.0																				
	Average depth	*mm*	26.0																				
	UCC	-	0.75																				
	DU_{lq}	-	0.69																				

settings, the use of sprinklers with hydraulic characteristics significantly different from the design specification due to inadvertent mixing of sprinklers, the use of sprinklers with significantly modified hydraulic characteristics due to wear and tear or routine maintenance issues could account for this observation.

Irrigation evaluation II: The second irrigation field evaluation event was conducted in a section of a grower's farm measuring 609.0ft along the mainline and 1530.0ft along the laterals. Each of the three irrigation uniformity evaluation test-plot has 49 rain gages arranged in grid squares (of 5ft×5ft), Figure 7a. The duration of the field evaluation was 7.0h. Table 2 summarizes the precipitation depths collected in each rain gage of the test-plots. They vary over a wide range, between a minimum of 13.0mm and a maximum of 28.0mm, with a field-scale average of 21.0mm. Although the data range suggests a fairly wide variation in the collected depths, as can be noted form Table 2 much of the data vary in a narrower band indicating higher field-scale irrigation uniformity. For each test-plot, the Christiansen's uniformity coefficient (UCC) and the low-quarter distribution uniformity (DU_{lq}) were computed with Eqs. 15 and 16 and are summarized in Table 2. The test-plot UCC values are 0.91, 0.91, and 0.87 for the upstream end, middle, and downstream end test-plots, respectively. Test-plot scale DU_{lq} varies in the range 0.84 to 0.88. The field-scale average UCC and DU_{lq} are 0.90 and 0.85, respectively. Note that the field-scale UCC is in the higher end of the recommended range for solid set sprinkler systems (Keller et al., 1980). In addition, the fact that the differences between the test-plot scale UCC and DU_{lq} values are relatively small indicate that the number of data points with extreme localized deviations from the average is small.

5.1.2 Maricopa study

Irrigation uniformity evaluations were conducted in the research farm of the Maricopa Agricultural Center of the University of Arizona. The layout of the sprinkler system used in the study is depicted in Figure 6. Three test-plots were installed distributed over the irrigated field, each representing an equal fraction of the irrigated field. A test-plot covers a rectangular area of 30.0ft×40.0ft, which is further discretized into 48 grid squares measuring 5ft×5ft, at the center of each is placed a rain gage

Table 2 Field data and uniformity computation for irrigation evaluation II, Yuma Valley Irrigation District

		Test-plot 1							Test-plot 2							Test-plot 3						
		Number of rain gages parallel to the laterals							Number of rain gages parallel to the laterals							Number of rain gages parallel to the laterals						
		1	2	3	4	5	6	7	1	2	3	4	5	6	7	1	2	3	4	5	6	7
		Collected depth (mm)							Collected depth (mm)							Collected depth (mm)						
Number of rain gages parallel to the mainline	1	13	18	20	20	20	20	20	18	18	19	20	20	22	25	18	-	-	-	-	-	15
	2	15	18	20	20	20	20	20	18	18	17	15	19	20	22	18	18	20	20	17	17	18
	3	20	20	20	20	23	23	20	18	17	18	18	20	20	20	19	18	18	19	20	20	20
	4	23	25	23	23	23	25	23	20	20	20	23	20	20	20	20	19	19	19	23	24	23
	5	23	23	23	23	23	20	23	25	20	22	22	23	20	20	24	18	18	20	23	28	27
	6	23	23	23	23	23	23	20	22	24	22	22	22	20	19	23	17	18	20	23	25	28
	7	20	20	20	18	15	20	20	28	28	23	25	19	22	20	20	17	20	18	23	27	26

		Unit	Test-plot 1	Test-plot 2	Test-plot 3
Average wind speed during irrigation test		*m/s*	1.2		
Duration of test irrigation event		*h*	7.0		
Test-plot Scale	Test-plot size	*ft*	30.0×35.0	30.0×35.0	30.0×35.0
	Farm block size	*ft*	510.0×609.0	510.0×609.0	510.0×609.0
	Average depth collected	*mm*	21.0	21.0	21.0
	UCC	-	0.91	0.91	0.87
	DU_{lq}	-	0.88	0.85	0.84
Field scale	Minimum depth collected	*mm*	13.0		
	Maximum depth collected	*mm*	28.0		
	Average depth	*mm*	21.0		
	UCC	-	0.90		
	DU_{lq}	-	0.85		

UCC = Christiansen's uniformity coefficient, DU_{lq} = low-quarter distribution uniformity, and test-plots 1, 2, and 3 represent the upstream end, middle, and downstream end test-plots, respectively, generally arranged along the field diagonal starting from the inlet end.

(Figure 7b). A total of five field evaluations were conducted with the same test-plot layout. The duration of the test irrigation event vary from 2.5h to 3.0h. The average wind speed over the duration of each of the irrigation evaluation events was less than 2.5m/s.

The precipitation depths collected during the first field evaluation event of the Maricopa study is summarized in Table 3. The average wind speed during the irrigation evaluation event is 2.2m/s and the duration of the irrigation event is 3.0h. The test-plot scale average depths collected vary in the narrow range of 9.9mm-11.1mm with a field-scale average of 10.5mm, suggesting a high field-scale irrigation uniformity. The test-plot scale uniformity indices vary in the range 0.87 to 0.90 for UCC and over a relatively wider interval of 0.77 to 0.86 for DU_{lq} (Table 3). Field-scale UCC and DUlq are 0.88 and 0.81, respectively.

Four additional field evaluations were conducted using the same test-plot layout (including the spatial distribution of test-plots over the irrigated field) and under comparable hydraulic and weather conditions. A summary of the test-plot scale and field-scale irrigation uniformity indices and the average precipitation depths collected are summarized in Table 4. The use of test-plot scale uniformity indices from different irrigation events to compute a field wide average irrigation uniformity (UCC and DU_{lq}) assumes that the hydraulic and weather conditions during the irrigation evaluation events did not show significant variation. The average wind speed is less than 2.5m/s and as will be described in section 5.3.1, the total dynamic head at the sprinkler system inlet varies in a narrow range of 139.0m to 144.0m. Hence the irrigation evaluations can be considered comparable with regard to system hydraulics and weather. However, the durations of the last two irrigation evaluation events were 2.5h, while those of the first three events are 3.0h. Hence, instead of average depths collected, the average application rate is computed as an indicator of the field wide average irrigation depth that can be applied by the sprinkler system, given the duration of an irrigation event.

As can be noted from Table 4, values of the test-plot scale uniformity indices are generally high and the field-scale averages (UCC of 0.86 and DU_{lq} of 0.78) are in the upper end of the recommended range for solid set sprinkler system. It can also be noted that uniformity estimates for the fourth field evaluation was relatively lower than those

Table 3 Field data and uniformity computation for irrigation evaluation I, Maricopa Agricultural Center

			Test-plot 1						Test-plot 2						Test-plot 3					
			Number of rain gages parallel to the laterals						Number of rain gages parallel to the laterals						Number of rain gages parallel to the laterals					
			1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6
			Collected depths (mm)						Collected depths (mm)						Collected depths (mm)					
Number of rain gages parallel to the mainline		1	12	11	10	8	8	10	12	11	9	7	8	9	15	11	9	10	10	12
		2	13	15	11	8	9	9	12	10	9	9	10	9	10	9	10	9	10	11
		3	14	12	10	9	11	10	11	10	10	11	10	10	9	9	10	10	11	12
		4	12	11	11	12	13	10	10	10	10	10	11	10	13	10	11	11	11	10
		5	14	13	11	12	11	12	10	11	11	11	10	11	10	11	11	11	11	11
		6	12	11	10	11	10	11	11	12	12	8	8	8	13	12	11	10	11	10
		7	12	12	10	9	10	14	11	12	10	7	7	8	12	11	10	10	9	9
		8	13	14	10	9	11	14	12	11	8	7	6	15	13	11	10	8	8	9
		Unit																		
Average wind speed during irrigation test		*m/s*	2.2																	
Duration of test irrigation event		*h*	3.0																	
Test-plot scale	Test-plot size	*ft*	35×40						35×40						35×40					
	Farm block size	*ft*	210×420						210×420						210×420					
	Average depth collected	*mm*	11.1						9.9						10.5					
	UCC	-	0.88						0.87						0.90					
	DU_{lq}	-	0.82						0.77						0.86					
Field scale	Minimum depth collected	*mm*	6.0																	
	Maximum depth collected	*mm*	15.0																	
	Average depth collected	*mm*	10.5																	
	UCC	-	0.88																	
	DU_{lq}	-	0.81																	

UCC = Christiansen's uniformity coefficient, DU_{lq} = low-quarter distribution uniformity, test-plot 1 is set in the field irrigated by the even-numbered laterals, test-plot 2 is installed in the field irrigated by the odd-numbered laterals but closer to the mainline, and test–plot 3 is set in the field irrigated by the odd-numbered laterals but further downstream from the mainline (Figure 6) obtained for the rest of the evaluations. Although average wind speed is slightly higher during this irrigation event (2.5m/s), perhaps the effect of factors other than wind speed (section 4.3) could be more significant.

The very high field-scale irrigation uniformity maintained over a series of irrigation events (Table 4) can be explained by the fact that the sprinkler system, described here, was specifically set up for research purpose and that care was exercised in ensuring proper installation and operation of the system. Considering this and the fact that the sprinkler system used in the study is smaller in size compared to a typical field sprinkler system in the Yuma Valley Irrigation District; the irrigation uniformity results

Table 4 Computed field-scale irrigation application uniformity and average applied depths, Maricopa Agricultural Center

	Christiansen's uniformity coefficient (-)				
	Test-plot scale				Field-scale
		Test-plot			
		1	2	3	
Irrigation evaluations	I	0.88	0.87	0.90	0.86
	II	0.90	0.89	0.92	
	II	0.84	0.89	0.88	
	IV	0.75	0.84	0.82	
	V	0.80	0.87	0.86	
	Low-quarter distribution uniformity (-)				
	Test-plot scale				Field-scale
Irrigation evaluations	I	0.82	0.77	0.86	0.78
	II	0.83	0.82	0.88	
	II	0.79	0.82	0.76	
	IV	0.69	0.73	0.72	
	V	0.71	0.78	0.75	
	Average application rate (mm/h)				
	Test-plot scale				Field-scale
Irrigation evaluations	I	3.7	3.3	3.5	4.3
	II	5.4	4.9	5.1	
	II	4.8	4.4	4.7	
	IV	4.5	4.0	4.1	
	V	3.8	4.0	3.8	
		Area weighing coefficient for each test-plot data (-)			Farm area, irrigated (*acre*)
		0.33	0.33	0.33	6.14

Area weighing coefficient for each test-plot is computed as the ratio of the area of the corresponding farm block to the total area of the field used in the study, irrigation evaluations I = data collected on June 27, 2012, II and III = data collected on June 28, 2012, and IV and V = data collected on June 29, 2012.

obtained in the Maricopa study are significant only to the extent that a sprinkler system with sufficiently large lateral and mainline diameter (typical of sprinkler systems in the Yuma area) can attain high levels of irrigation uniformity provided the system is well maintained and is operated under low wind speed conditions.

5.2 Field measured hydraulic data

The hydraulic data presented here consists of pressure head and discharge measurements made in an experimental field-scale sprinkler system with double-line laterals layout configuration (Figure 6, section 4.2). As described above, the field evaluation was conducted at the Maricopa Agricultural Center of the University of Arizona and the primary objective was to collect hydraulic data for model evaluation purposes: verification of the component of the mathematical model developed for hydraulic analysis of sprinkler systems with double-line laterals layout configuration. A detailed description of the hydraulic, geometric, and topographic attributes of the sprinkler system used in the study is presented in the methodology section. Three sets of hydraulic data, labeled here as data sets I, II, and III, were collected during the field evaluations. All the data sets consist of measured pressure head profiles along the main. To be specific these measurements were made, on the laterals, at a distance of one sprinkler spacing from the main. In addition, data sets I, II, and III consist of measured pressure head profiles along laterals #4, #7, #9, respectively (Figure 6). Inlet discharges measured at the inlet of laterals #4 and #9 during two field evaluations events (Data sets I and III) were also used in the model evaluation.

The hydraulic, geometric, and topographic input data used for model evaluation is summarized in Table 5. The total dynamic head at the mainline inlet is computed as a function of measured elevation and pressure head and computed velocity head at the system inlet (based on pipe geometry and approximate flow rate derived as a function of measured lateral discharges). The friction calculation equation used in model evaluation is that of Darcy-Weisbach. The pipe absolute roughness given in Table 5 is obtained from Keller and Bliesner (1990) as a function of pipe material: aluminum pipe. Values of the local head loss coefficient for the branch and line-flow at the lateral-sprinkler riser pipe and mainline lateral junctions were also obtained from Keller and Bliesner (1990) as a function of pipe material, diameter, and type of pipe appurtenance.

Table 5 Input data for model evaluation and simulation examples

Type of input data		Unit	Model evaluation	Data used in simulation examples	
				Single-line laterals	Double-line laterals
Sprinkler spacing[1]		*m*	9.14	9.14	9.14
Coefficient of sprinkler $q(h_s)$ function, α_1,[2]		$L/s/m^{\alpha 2}$	0.0258	0.0125	0.0125
Exponent of sprinkler $q(h_s)$ function, α_2,[2]		*(-)*	0.502	0.521	0.521
Lateral spacing[3]		*m*	12.19	10.67	10.67
Lateral length		*m*	192.03	374.8	374.8
Lateral diameter[4]		*mm*	76.2	76.2	-
Slope along laterals[5]		*(-)*	±0.0001	-	-0.00055
Mainline length		*m*	64.01	149.4	160.0
Mainline diameter		*mm*	152.4	203.2	203.2
Mainline slope		-	-0.0003	0.0	0.0
Total dynamic head (mainline inlet) [6]		*m*	139.0/144.0	158.0	158.0
Pipe absolute roughness, (aluminum pipe) *(e)*		-	0.127	0.127	0.127
Local head loss coefficient at lateral and riser pipe coupling	Branch flow	-	1.3	1.3	1.3
	Line flow	-	0.7	0.7	0.7
Local head loss coefficient at mainline and lateral coupling	Branch flow	-	1.0	1.0	1.0
	Line flow	-	0.5	0.5	0.5

[1]The first sprinkler is located at full spacing form the lateral inlet; [2]Coefficient and exponent of sprinkler pressure head-discharge function; [3]Considering the data used for model evaluation, the first lateral is installed at a distance of 3.05m from the pump; [4]Lateral diameter used in the simulation example with double-line laterals layout configuration vary along the laterals (between 0-128.0m is 76.2mm, between 128.0m-228.5m is 63.5mm, and between 228.5m-374.8m is 50.8mm); [5]Lateral slope used for system simulation with single-line laterals layout configuration vary along the laterals (between 0-128.0m is -0.3%, between 128.0-256.0m is 0.0%, and between 256.0-374.8m is 0.5%); and [6]Considering the data used for model evaluation, the total dynamic head imposed at the system inlet for data set I is 139.0m and for data sets II and III it is 144.0m.

5.3 Hydraulic modeling

A limited evaluation of the component of the model, developed for hydraulic analysis of a field-scale sprinkler system with double-line laterals layout configuration, is presented here. The model is then used to simulate the hydraulics of the field-scale sprinkler irrigation system used in the study. In addition, a discussion on the sensitivity of the sprinkler irrigation system hydraulics to changes in hydraulic, geometric, and topographic variables is presented. Hydraulic simulation examples are also presented in order to highlight the practical applications of the model.

5.3.1 Model evaluation with field data

Model evaluation is based on a comparison of measured and computed hydraulic grade line (HGL) along the main and laterals and lateral inlet discharges. Because discharge measurements were available only at the lateral inlets, computed energy grade lines (EGL) cannot be compared with measured data. However, velocity heads are very small (the maximum value occurring at the lateral inlet can be shown to be about 3.0cm, which is less than 0.1% of measured pressure heads) and as a result the difference between HGL and EGL is negligible. Therefore, a comparison of the measured and computed HGL and lateral inlet discharges was considered here as a satisfactory criteria for model evaluation.

A comparison of the simulated and measured HGL along the main and laterals for data sets I, II, and III are depicted in Figures 8a-8f. The results presented in Figures 8a-8f are computed based on simulations with values of system total dynamic head, imposed at the inlet, equal to 139.0m for data set I and 144.0m for data sets II and III. For all the three irrigation evaluations the measured HGL data closely matches the simulated values. For each irrigation evaluation, the minimum, maximum, and average relative difference between measured and computed pressure heads along the mainline and the laterals are summarized in Table 6. The error in pressure head prediction along the laterals vary between a minimum value of 0.31% for lateral #9 and a maximum value of 3.28% for lateral #7, with an overall average of 1.49% (Table 6). The error in the computed mainline pressure head vary in the range 0.32% to 11.59%, with an overall average value of 2.02% (Table 6). Lateral inlet discharge prediction errors vary between a minimum value of 9.9% at the inlet of lateral #4 (Data set I) and a maximum value of 14.9% at the inlet of lateral #9 (Data set I), Table 6. The overall average error in lateral inlet discharge prediction is 11.8%.

The results summarized in Figure 8 and Table 6 show that the hydraulic model predicted pressure head profiles along the laterals and the main accurately. On the other hand, model predicted lateral inlet discharges show larger error than pressure head estimates. However, considering the relatively low precision of the flow meter used in the study (10 GPM), it can be noted that some fraction of the error in lateral inlet discharge estimates (Table 6) can be accounted for by measurement error.

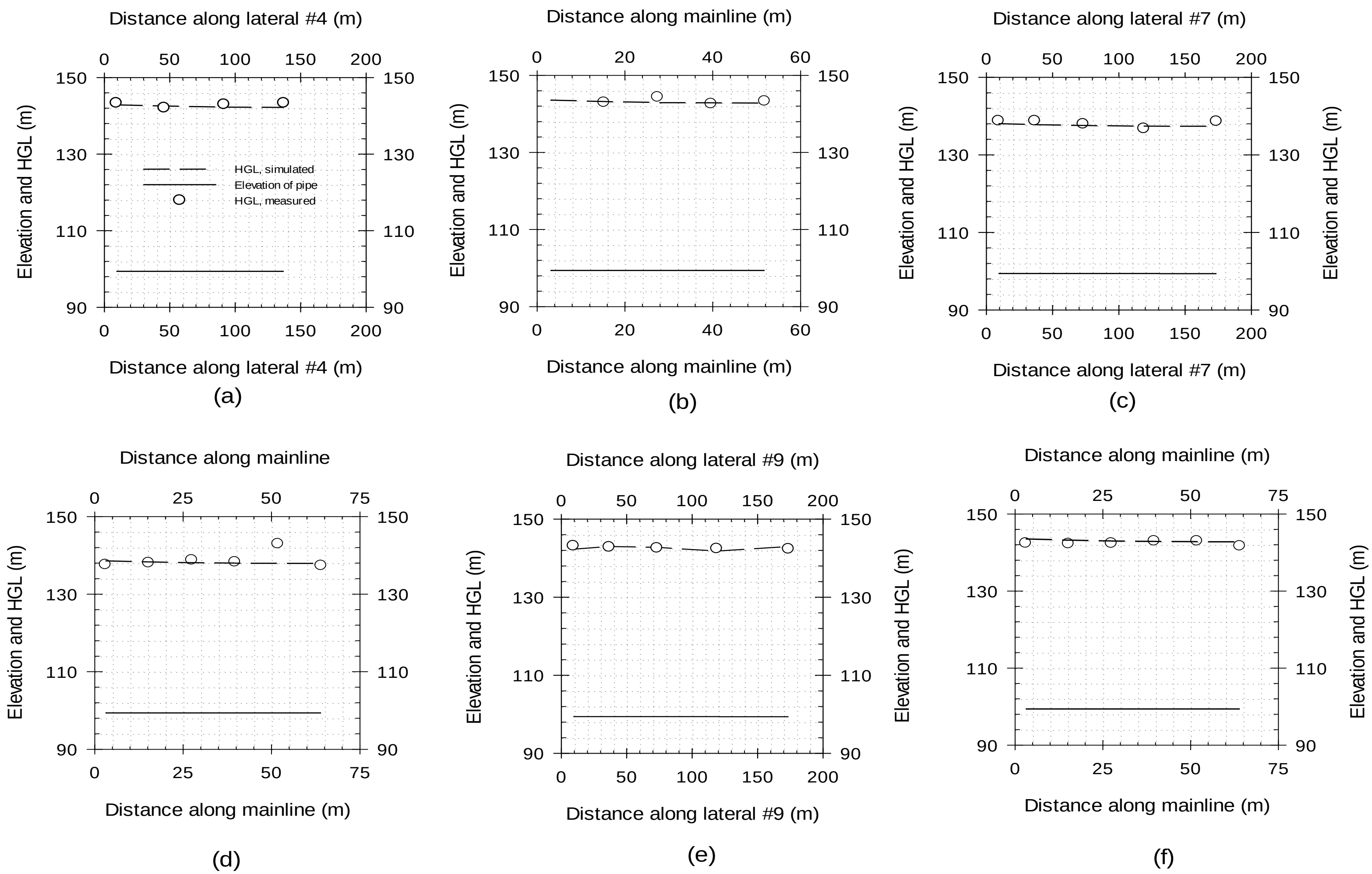

Figure 8 Comparison of model predicted and field observed hydraulic grade lines (HGL): (a) Along lateral #4, Data set I; (b) Along mainline, Data set I; (c) Along lateral #7, Data set II; (d) Along mainline, Data set II; (e) Along lateral #9, Data set III; and (f) Along mainline, Data set III

The fact that the simulation results were obtained without the need for model calibration (based only on a generic set of literature data for pipe absolute roughness and local loss coefficients) suggests that the computational algorithm implemented in the hydraulic model is accurate. Note that both the measured and computed pressure heads along the laterals and the mainline as well as the corresponding HGL’s show very small spatial variation (Figure 8). The fact that the maximum slope of the computed energy grade lines (EGL’s) and the maximum velocity head along the laterals are very small, about 0.5% and 3.0cm, respectively; shows that the lateral diameter in the test farm (which is 76.2mm) is sufficiently large to keep the friction head loss, velocity head, and the local head losses along the laterals very small. Since elevation differences in the test-farm have negligible effect on pressure variation, the very small energy loss within the sprinkler system should imply a uniform sprinkler pressure head and hence discharge variation over the irrigated field. This implies that the relatively large pipe diameter, and the resultant hydraulics, is an important contributing factor to the high level of application uniformity observed during the test irrigation events. Although large diameter pipes have the added advantage of minimizing operational costs of the system; they will result in higher installation costs.

Table 6 Comparisons of computed and measured pressure heads and discharges

Computed and measured pressure head along laterals and lateral inlet discharges

Lateral #	Error, nodal pressure head				Error, inlet discharge		
	Minimum (%)	Maximum (%)	Average (%)	Over all average (%)	Data set I (%)	Data set III (%)	Overall average (%)
4	0.75	2.96	1.71		9.9	10.9	
7	1.02	3.28	2.07		-	-	
9	0.31	1.98	1.10		14.9	11.5	
				1.49			11.8

Computed and measured pressure head along the mainline

Lateral #	Error, nodal pressure head			
	Minimum (%)	Maximum (%)	Average (%)	Over all average (%)
Data set I	0.47	3.17	1.34	
Data set II	0.57	11.59	3.14	
Data set III	0.32	2.68	1.58	
				2.02

Error = |Measured –Computed|×100/ Measured; Average = arithmetic average of the errors computed for each measurement station along a lateral or the mainline; Overall average = the error averaged over all pertinent data sets

5.3.2 Field-scale hydraulic simulation

The field-scale sprinkler system used in the Maricopa field evaluation is described in section 4.2 and the system layout is depicted in Figure 6. Related geometric, hydraulic, and topographic data used in the field-scale hydraulic simulation is presented in Table 5. The mathematical model developed as part of the current study generates various types of output data, including: hydraulic characteristics curves for each mainline outlet and for the system inlet, energy and hydraulic grade lines along the main and each of the laterals, discharges at each of the computational nodes along the main and the laterals, and sprinkler pressure heads and discharges (Zerihun and Sanchez, 2012). However, in subsequent discussion only a summary of the model outputs that have direct significance from irrigation management perspective are presented: the field-scale spatial distribution of sprinkler pressure heads and discharges and the corresponding system hydraulic characteristic curves. Although the total dynamic head for the three hydraulic evaluations vary from 139.0m to 144.0m, only a simulation of the irrigation evaluation events with a total dynamic head of 144.0m is presented in subsequent discussion.

The spatial distribution of sprinkler pressure heads and discharges obtained through hydraulic simulation are summarized in Figures 9a and 9b, respectively. The two halves of the sprinkler system considered here are identical in terms of their geometric and pipe hydraulic characteristics, but are slightly different in the lateral slopes, with laterals irrigating one-half of the field installed on a surface with a slope of -0.01% and the other half installed on a slope of 0.01% (Table 5). However, the effects of the difference in slope on the sprinkler pressure head range, the locations in the field of the maximum and minimum pressure heads, and the spatial distribution of pressure head are negligible; hence for practical purposes the pressure head and discharge distribution patterns in one half of the field can be considered mirror images of those of the other half and vice-versa. Subsequent discussion will, therefore, focus on describing the pressure head and discharge distribution patterns for one-half of the field, implying that about the same inferences and observations can be made for the other half as well.

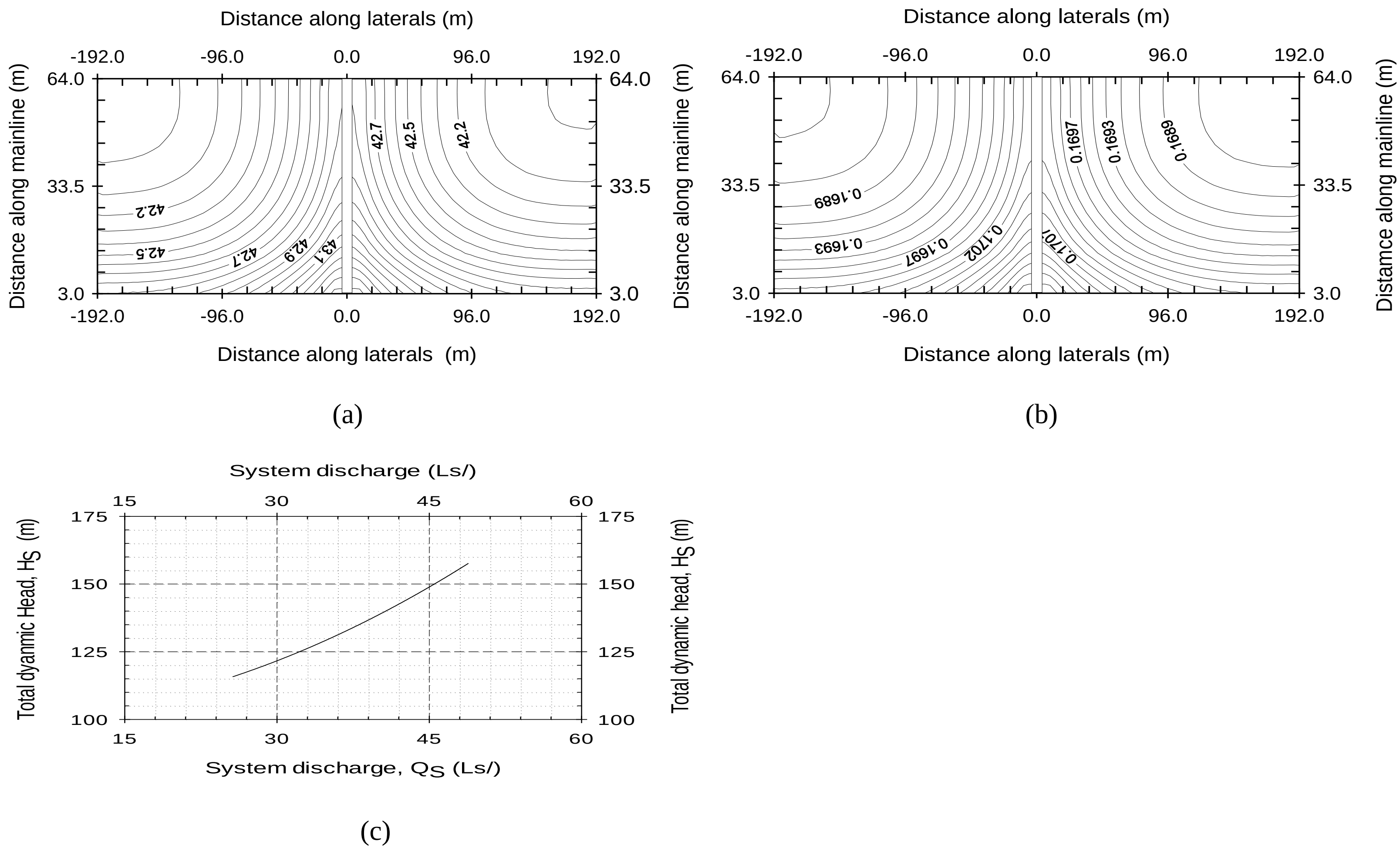

Figure 9 Hydraulic simulation of the field-scale sprinkler system with double-line laterals field layout configuration used in the Maricopa field study: (a) Spatial distribution of sprinkler pressure heads, (b) Spatial distribution of sprinkler discharges, and (c) System hydraulic characteristics (Note that the positive and negative algebraic signs in Figures 9a and 9b are meant to emphasize that distance measurement were made in opposite spatial direction with reference to the mainline)

Considering either half of the field, it can be noted that the maximum sprinkler pressure head (43.5m) and maximum discharge (0.1715L/s or 2.719GPM) occur at the system inlet and the minimum pressure head (42.1m) and the minimum sprinkler discharge (0.1685L/s or 2.671GPM) occur near the field corner opposite to the inlet. The field-scale average sprinkler pressure head (considering the same fraction of the irrigated field) and discharge is about 42.5m and 0.1694L/s (2.686GPM), respectively. The range of sprinkler pressure head and discharge variation over the irrigate field is 3.5% and 1.7% of the average, respectively. Considering an average pressure head close to the design pressure head, the result suggests that the field-scale sprinkler pressure head (and hence discharge) variations are well within the recommended range for satisfactory sprinkler irrigation system uniformity.

The spatial distribution of sprinkler pressure head over the upper quarter of the field (hydraulically speaking) shows the highest degree of sensitivity to distance, from sprinkler system inlet, along both coordinate axes (parallel and normal to the main), Figure 9a. Note that this is typical of a field-scale sprinkler system with level or nearly level field surface and spatially invariant lateral diameter, common in the Yuma area. On the other hand, in the lowest quarter of the field, pressure head and discharge variation exhibits the least sensitivity to distance measured from the system inlet. However, in the other two quarters of the field, sprinkler pressure heads and discharges show appreciable levels of sensitivity to distance in only one direction (in a direction parallel or perpendicular) to the laterals.

The lateral inlet discharges vary between 3.55L/s (56.3GPM) to 3.58L/s (56.7GPM). The system discharge is 42.69L/s (676.8GPM) with a total dynamic head of 144.0m, which is specified at the input (Table 5). The system discharge is almost equally divided between the two halves of the irrigated field, this is due to the fact that the hydraulic and geometric characteristics of the two subsystems are nearly identical and that the differences in land slope is negligible to have a significant effect on the hydraulics of the sprinkler system.

5.3.3 Sensitivity analysis

The preceding section presents the most significant model output (from irrigation management perspective) obtained through hydraulic simulation of the field-scale sprinkler system used in the current study. An analysis of the sensitivity of the hydraulics of a field-scale sprinkler system with single-line lateral layout configuration to changes in total dynamic head, lateral diameter, lateral slope, and pipe absolute roughness was presented by Zerihun et al. (2011). The most important result was that given the pipe diameters that are in common use in the Yuma Valley Irrigation District, system hydraulics is dominated by pipe diameter and it exhibits little sensitivity to significant variations in land surface slope and pipe absolute roughness. This suggests that the hydraulic design of the field-scale sprinkler system considered in the study is robust. In the current analysis, the sensitivity of the hydraulics of a sprinkler system with double-line laterals layout configuration to changes in the total dynamic, lateral diameter, lateral slope, and pipe absolute roughness is evaluated. A one-dimensional sensitivity analysis was conducted, in which at any one time the value of only one variable is varied and all other factors are kept constant at the level used in the field-scale hydraulic simulation of the sprinkler system (Table 5).

Total dynamic head at the system inlet

In order to evaluate the effects, of variation in the total dynamic head, on the field-scale spatial distribution of sprinkler pressure head and discharge; the total dynamic head was varied in the range 134.0m to 154.0m in increments of 10.0m. Note that 144.0m is the total dynamic head used in the actual system in two of the field evaluations (Table 5). The resulting spatial distribution of pressure head is depicted in Figures 10a-10c and sprinkler discharges are shown in Figures 10d-10f. Overall, the locations of the maximum and minimum sprinkler pressure heads and discharges within the irrigated field, the spatial variation patterns for both the sprinkler pressure heads and discharges, as well as the ranges of variation of sprinkler pressure head and discharge expressed as a percent of

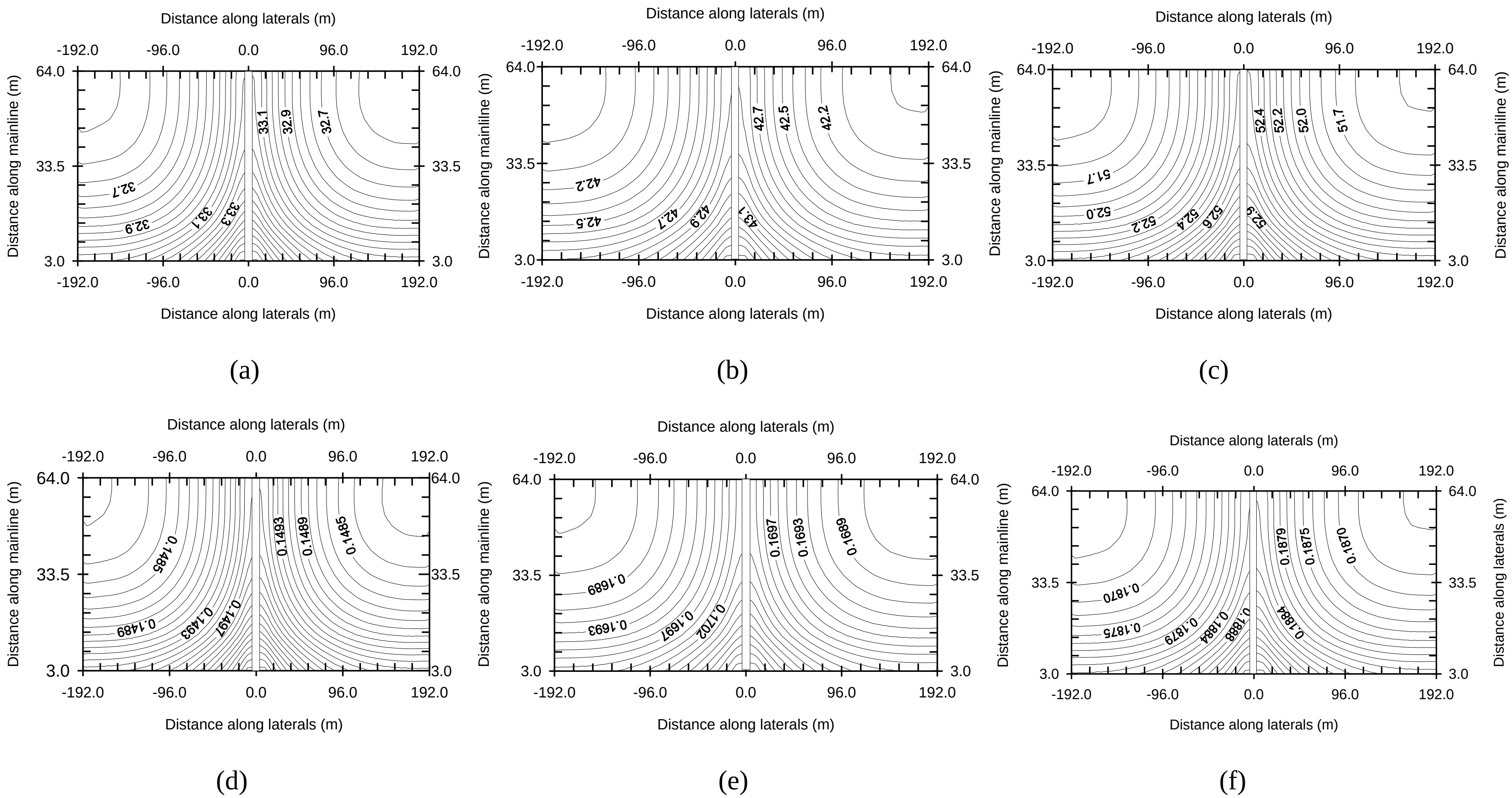

Figure 10 The sensitivity of field-scale spatial distribution of sprinkler pressure head (m) to total dynamic head (H_s): (a) H_s = 134.0m, (b) H_s = 144.0m, and (c) H_s = 154.0m; the sensitivity of field-scale spatial distribution of sprinkler discharge (L/s) to total dynamic head: (d) H_s = 134.0m, (e) H_s = 144.0m, and (f) H_s = 154.0m

the field-scale averages show no sensitivity to changes in the total dynamic head at the system inlet. However, the actual values of the sprinkler pressure heads and discharges show significant levels of sensitivity to changes in total dynamic head. The field-wide average sprinkler pressure head for a total dynamic head of 134.0m is 32.9m (Figure 10a). This is appreciably lower than the field-scale average pressure head values of 42.5m and 52.1m for systems with total dynamic head of 144.0m and 154.0m, respectively (Figures 10b and 10c).

As would be expected the sensitivity of sprinkler discharges to changes in total dynamic head is less pronounced than pressure heads, nonetheless, significant. Overall the absolute values of sprinkler pressure heads and discharges are increasing functions of changes in total dynamic head. The practical implication of this result is that maintaining the accuracy of pump pressure gages and/or flow meters is important for satisfactory irrigation system management.

Lateral diameter

The results of field-scale hydraulic simulation presented in the preceding section (section 5.2.3) show that the diameter of the field-scale sprinkler system used in the study (76.2mm) is already sufficiently large to keep energy loss within the laterals very small. Hence, the hydraulics of the sprinkler system should not show any appreciable levels of sensitivity to further increases in lateral diameter. In subsequent analyses only commercially available aluminum pipes with diameters smaller than 76.2mm (3.0”) are considered. Figures 11a-11f depict the simulated spatial distribution of field-scale sprinkler pressure heads and discharges for lateral diameters of 44.45mm (1.75”) and 50.8mm (2.0”) along with those simulated for a lateral diameter of 76.2mm (3.0”). As can be noted from Figures 11a-11f, changes in lateral diameter have a significant effect on the pattern of distribution of sprinkler pressure heads and discharges as well as on their ranges of variation. However, variations in lateral diameter do not affect the location of the maximum and minimum sprinkler pressure head and discharge in the field. As lateral diameter is reduced from 76.2mm to 50.8mm the range of variation of the field-scale sprinkler pressure head increased from 1.5m to 5.6m. Further decrease in lateral diameter to 44.45mm results in a significant increase in the range of variation of the field-scale sprinkler pressure head to 9.4m. Figures 11a-11c also depict that as the lateral

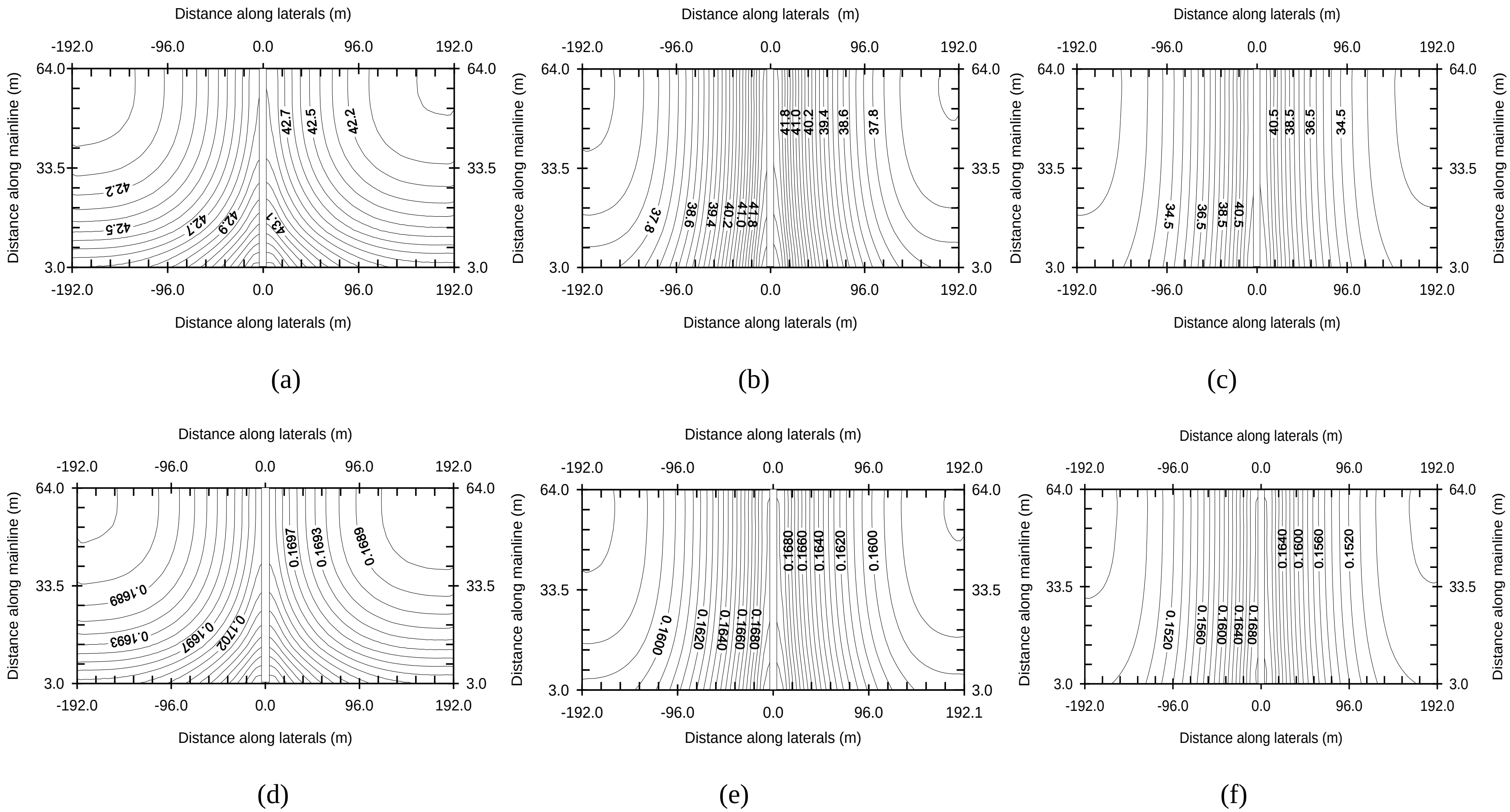

Figure 11 The sensitivity of field-scale spatial distribution of sprinkler pressure head to lateral diameter (D_l): (a) D_l = 76.2mm, (b) D_l = 50.8mm, (c) D_l = 44.45mm; and the sensitivity of field-scale spatial distribution of sprinkler discharge (L/s) to D_l: (d) D_l = 76.2mm, (e) D_l = 50.8mm, and (f) D_l = 44.45mm

diameter is reduced from 76.2mm to 50.8mm and then 44.45mm, the sprinkler discharge contours become nearly parallel to the mainline, the implication being the spatial distribution of sprinkler discharges become increasingly dominated by lateral diameters. In light of the significance of pipe diameter on friction and local head losses (Eqs. 6, 12, and 13), the observed level of sensitivity of field-scale spatial distribution of pressure heads and discharges is consistent with hydraulic theory.

Although the location of the minimum and the maximum sprinkler discharges within the irrigated field is unaffected by changes in lateral diameter, the spatial distribution patterns of sprinkler discharges and their ranges of variation exhibit significant sensitivity to lateral diameter (Figures 11d-11f). In a manner similar to what has been observed in relation to sprinkler pressure heads (Figures 11a-11c), as the lateral diameter is reduced, the field-scale distribution of sprinkler discharges become increasingly dominated by the effects of lateral diameter.

Lateral slope

In order to evaluate the effects of changes in lateral slope on the spatial distribution and range of variation of sprinkler pressure heads and discharges simulation is conducted for two additional scenarios: one in which the field surface has a constant longitudinal slope (slope in the direction parallel to the laterals) of 0.1% and another one of 0.3%. Note that this implies one half of the field is irrigated with laterals running uphill with a slope of 0.1% or 0.3% and the other half is irrigated by laterals with a longitudinal slope of -0.1% and -0.3%. Although irrigated fields with 0.1% slope are common in the Yuma Valley, the large slope of 0.3% is used because of its theoretical appeal. The sprinkler pressure head and discharge distribution resulting from a relatively steep negative slope (considering one-half of the field irrigated) is unique and lends itself to qualitative verification based on intuitive hydraulic reasoning.

Simulated pressure head and discharge distributions for a field surface with longitudinal slopes of 0.01% (actual system used in the field study, Table 5), 0.1%, and 0.3% are depicted in Figure 12a-12f. Considering the scenarios with longitudinal slopes of 0.01% and 0.1%, the location of the maximum and minimum sprinkler pressure heads within the irrigated field are essentially the same. However, the pressure head contours for the field with a longitudinal slope of 0.1% are slightly shifted to the right compared

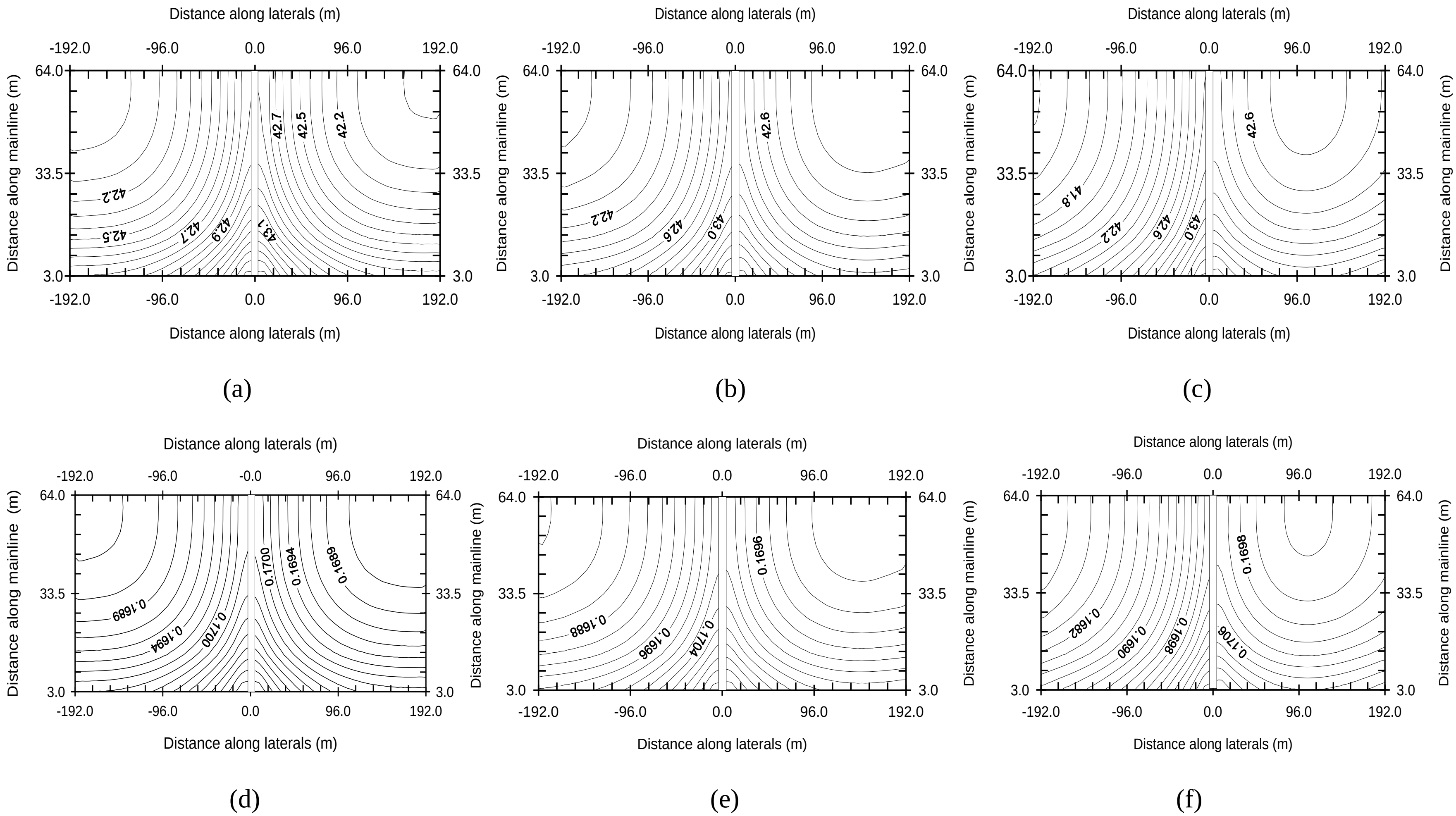

Figure 12 The sensitivity of field-scale spatial distribution of sprinkler pressure head (m) to lateral slope (S_o) : (a) $S_o = \pm 0.0001$; (b) $S_o = \pm 0.001$, (c) $S_o = \pm 0.003$; and the sensitivity of field-scale spatial distribution of sprinkler discharge (L/s) to lateral slope: (d) $S_o = \pm 0.0001$, (e) $S_o = \pm 0.001$, (f) $S_o = \pm 0.003$

to that for a field with a 0.01% slope (Figure 12b). On the other hand, when the longitudinal slope of the field is increased to 0.3%, in the part the irrigated field where laterals run uphill, the locations of the maximum and the minimum sprinkler pressure heads within the field remain essentially unchanged (compared to the scenarios with longitudinal slopes of 0.01% and 0.1%, Figure 12a and 12b). However, the range of variation of the field-scale sprinkler pressure head is larger for 0.3% slope, reflecting the effect of increased lateral slope on pressure head. Considering the part of the irrigated field with a lateral slope of -0.3%, the sprinkler pressure head decreases over the upper 110.0m length of the field and then increases in the field segment downstream (Figure 12c). While the maximum sprinkler pressure head occurs at the system inlet, the minimum pressure head occurs along the distal end lateral at about 110.0m from its inlet end. The observed pattern of sprinkler pressure head distribution can be explained by the interactive effects of lateral slope and energy loss due to friction and local losses along laterals (Zerihun et al., 2011).

The effect of lateral slope on the spatial distribution pattern of sprinkler discharges and the location of the maximum and minimum sprinkler discharges is about the same as that observed above in relation to sprinkler pressure heads (Figures 12d-12f). As will be shown in Figure 14, the system characteristics curve does not show appreciable sensitivity to changes in lateral slope within the range considered in the current study. Overall, the results indicate that the system hydraulic characteristics show very little sensitivity to significant changes in field slope, which confirms the preceding observation that the hydraulics of the field-sprinkler system used in the study is dominated by the relatively large pipe (mainline and lateral) diameters. Note that this is typical for sprinkler systems in the Yuma Area.

Pipe absolute roughness

The friction head loss computed as a function of pipe absolute roughness of 0.127 (value recommended for aluminum pipes, Table 5) is very small. Hence, the hydraulics of the sprinkler system used in the field evaluation (Figure 6) should be virtually insensitive to lower values of pipe absolute roughness. In the current study, the field-scale spatial distribution of sprinkler pressure heads and discharges were evaluated

only with respect to pipe absolute roughness values that are significantly larger than 0.127: 0.254 and 0.381, representing a 200% and 300% increases, respectively.
As can be noted from Figures 13a-13f, increasing pipe absolute roughness by 300% from 0.127 to 0.381 has virtually no effect on the location of the maximum and minimum sprinkler pressure heads and discharges within the field and also in the patterns of the sprinkler pressure head contours. This is consistent with the fact that the changes in absolute roughness affect the entire sprinkler system network uniformly. As would be expected the increase in pipe absolute roughness resulted in a slight increase in the rate with which sprinkler pressure heads and corresponding discharges decrease with distance from the system inlet (Figures 13a-13f). Nonetheless, the changes in sprinkler pressure head and discharge are very small compared to the respective increase in pipe absolute roughness. Again the main reason for this is that the relatively large pipe diameter dominates the sprinkler system hydraulics. The effect of pipe diameter compared to hydraulic roughness characteristics of the pipe can be readily evident by examining the energy equation (Eq. 4, 6, and 12): which shows that pipe diameter has a strong nonlinear effect on the energy equation compared to hydraulic roughness which has a much more milder nonlinear effect compared to pipe diameter. As can be noted from Figure 14, the system hydraulic characteristics curve did not show appreciable sensitivity to changes in absolute roughness. This is consistent with preceding observation that the sprinkler pressure head was only slightly affected by changes in absolute roughness (Figure 13a-13c). Overall, the results suggest that the hydraulic characteristics of the sprinkler system considered here are virtually insensitive to significant changes in pipe hydraulic resistance properties.

Sensitivity of sprinkler system hydraulic characteristics: The sensitivity of the sprinkler system hydraulic characteristics to changes in lateral diameter, pipe absolute roughness, and lateral slope is summarized in Figure 14. Consistent with the preceding discussion, the sprinkler system hydraulic characteristics shows little sensitivity to significant changes in laterals slope and pipe absolute roughness. However, the hydraulic characteristics curve of a sprinkler system with lateral diameter of 50.8mm shows that for a given discharge at the system inlet, Q_s, the corresponding total dynamic head, H_s, is appreciably higher than the total dynamic head for a sprinkler system with lateral

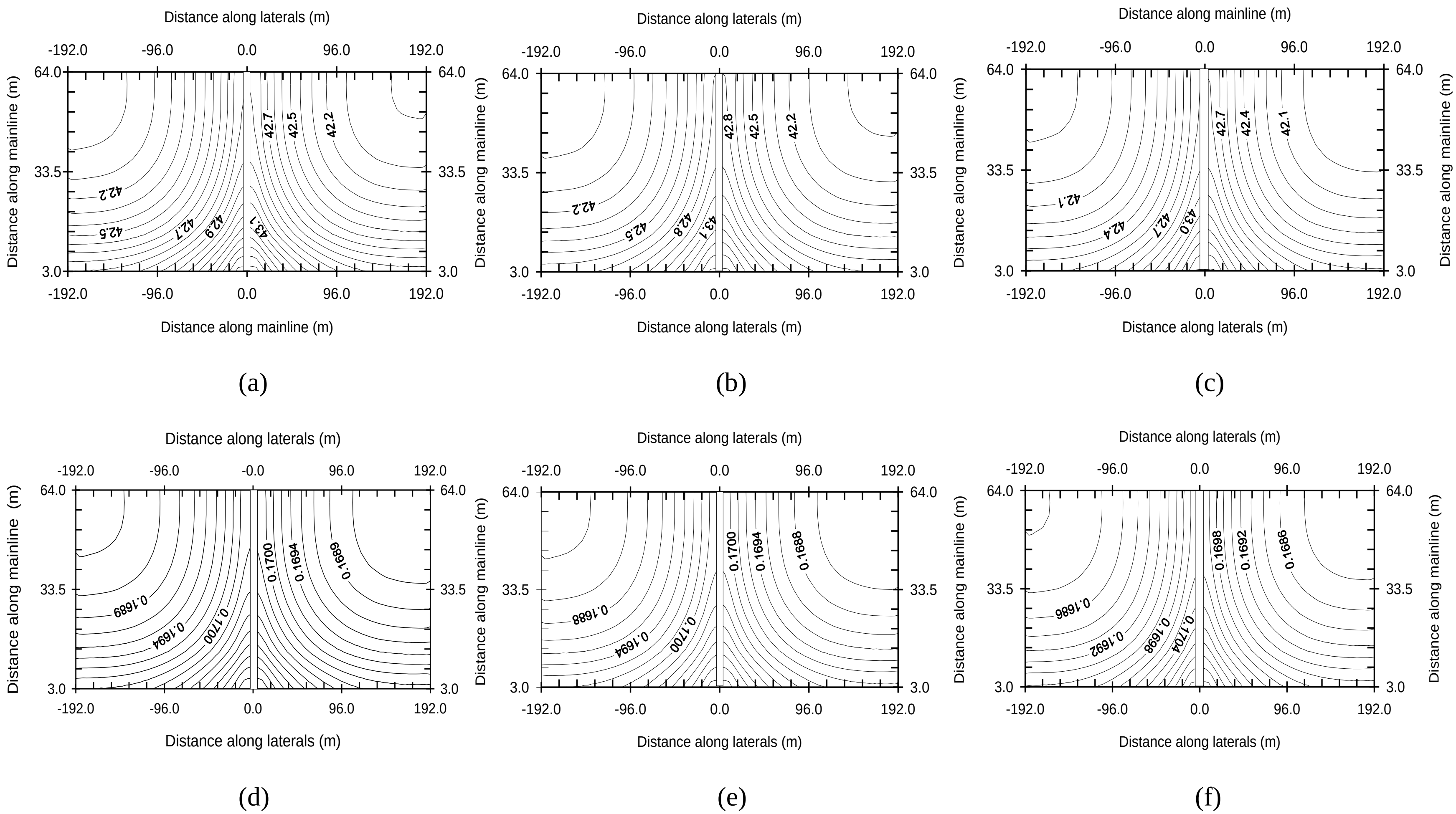

Figure 13 The sensitivity of field-scale spatial distribution of sprinkler pressure head (m) to pipe absolute roughness (*e*): (a) *e* = 0.127, (b) *e* = 0.254, (c) *e* = 0.381; and the sensitivity of field-scale spatial distribution of sprinkler discharge (L/s) to pipe absolute roughness: (d) *e* = 0.127, (e) *e* = 0.254, (f) *e* = 0.381

diameter of 76.2mm. Further reduction in lateral diameter to 44.45mm results in a system hydraulic characteristics curve that is significantly higher than that obtained for lateral diameters of 76.2mm and appreciably higher than that obtained for a lateral with a diameter of 50.8mm. Note that these results are consistent with intuitive hydraulic reasoning and observations noted above with regard to the sensitivity of sprinkler pressure and discharge to lateral diameter. As can be noted from Figure 14, if all the geometric, hydraulic, and topographic attributes of the sprinkler system is kept constant (at the level given in Table 5) and only the lateral diameter is varied, then the system with the smallest lateral diameter requires the largest total dynamic head (and power) to deliver a given discharge.

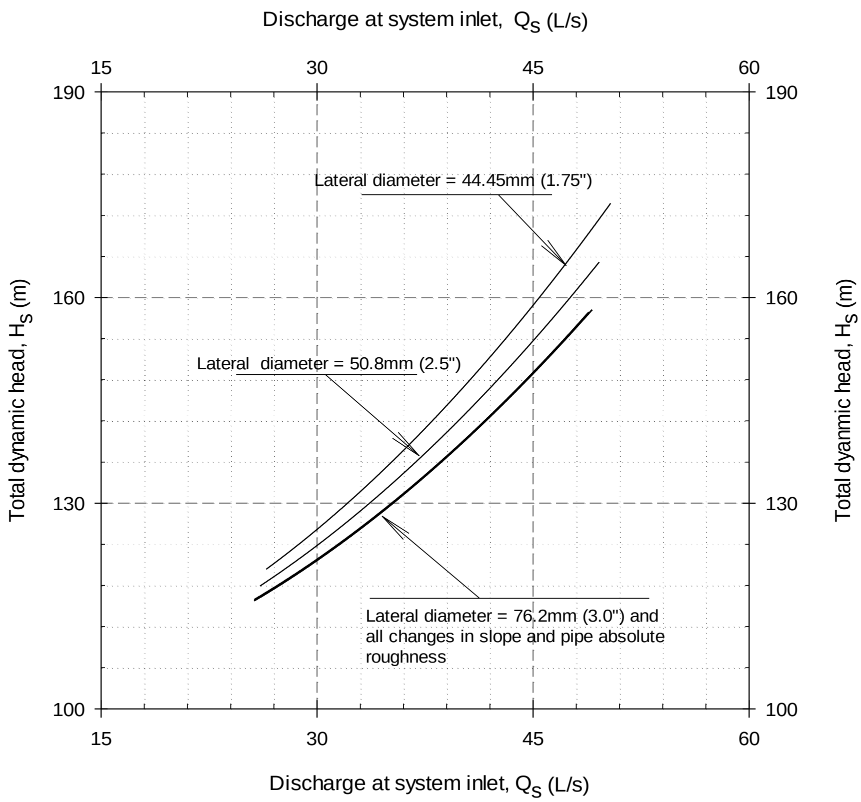

Figure 14 Sprinkler system hydraulic characteristics

5.3.4 Model applications

With the aim of highlighting the practical application of the model, described here, in the context of sprinkler systems with variable topographic and geometric characteristics, results of field-scale hydraulic simulations for systems with both single-line and double-line laterals is presented in Figure 15. The input data sets used in the simulation example are summarized in Table 5. A summary of the hydraulic simulation outputs with direct significance in terms of their effect on irrigation uniformity is presented and discussed in subsequent sections.

Single-line laterals

The irrigated field considered in this example has a rectangular shape with a width of 149.4m and a length of 374.8m (Table 5 and Figures 15a and 15b). The field has no cross-slope. Note that the term cross-slope here refers to the land surface slope in a direction parallel to the shorter side of the field. Longitudinally (referring to the direction parallel to the longer field dimension), the field is comprised of three parcels (shown in Figures 15a and 15b separated by dashed lines) each with a constant slope yet different from an adjacent parcel: the upper 128.0m reach of the field has a uniform slope of -0.3%; the middle section of the field (spanning between 128.0m and 256.0m) is level; and the lower section of the field (between 256.0m and 374.7m) has a slope of 0.5% (Table 5). The sprinkler irrigation system considered here consists of a 149.4m long mainline installed across the head end of the irrigated field with a constant elevation of 100.0m (0.0% slope). It is comprised of 203.2mm diameter aluminum pipe sections with an absolute (equivalent sand grain) roughness of 0.127mm. The mainline has fourteen off-take nodes set at a regular spacing of 9.14m, each supplying water to 374.8m long laterals. Since the laterals run normal to the mainline, following the spatial variation of the longitudinal slope of the field, each lateral has three distinct segments with different slopes. All the laterals are comprised of aluminum pipe sections with 76.2mm diameter and the same hydraulic resistance characteristic as the mainline. Each lateral has 41 sprinklers installed at regular spacing of 9.14m. The local head loss coefficients and the parameters of the sprinkler pressure head-discharge function are also summarized in Table 5. The total dynamic head at the system inlet is set at 158.0m, the same level as that used in the simulation example presented in the companion paper.

The simulated spatial distribution of sprinkler pressure heads and discharges for the example with single-line laterals are summarized in Figures 15a and 15b,

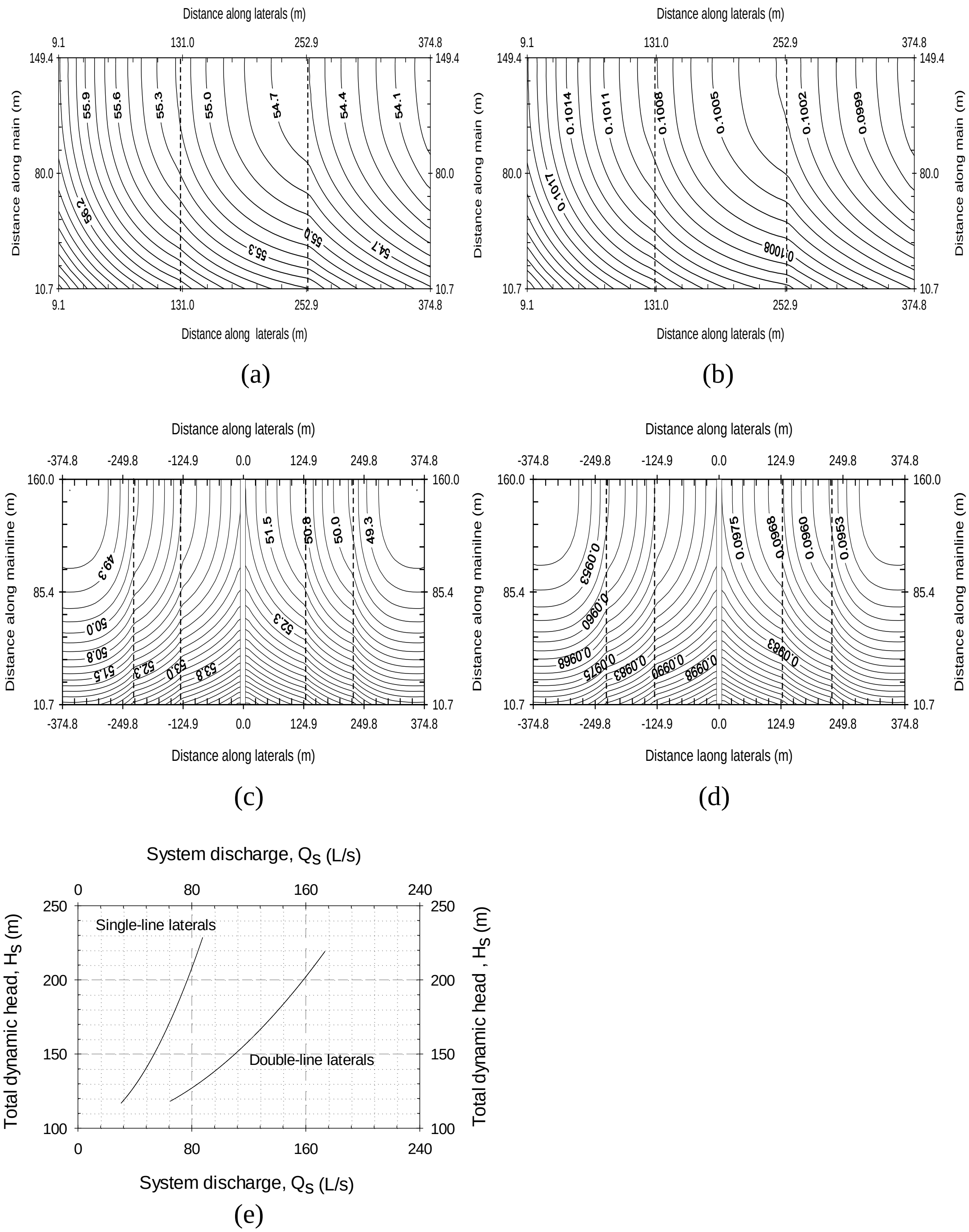

Figure 15 Hydraulic simulation example: (a) Sprinkler pressure head distribution (single-line laterals with variable slope), (b) Sprinkler discharge distribution (single-line laterals with variable slope), (c) Sprinkler pressure head distribution (double-line laterals with variable diameter), (d) Sprinkler discharge distribution (double-line laterals with variable diameter), and (e) System hydraulic characteristics for both single-line and double line laterals

respectively. As can be noted from Figure 15a, the maximum sprinkler pressure head occurs at the inlet end of the sprinkler system (57.2m) and the minimum occurs at the field corner opposite the system inlet (53.9m). The range of field-wide pressure head variation is 5.9% of the field-scale average (55.1m). Considering the standard recommendations for sprinkler lateral and mainline design (Keller and Bleisner, 1990; Martin et al., 2007b), this represents a highly uniform field-scale pressure head distribution.

Considering the direction parallel to the main (Figure 15a), the sprinkler pressure head distribution over the upper half of the field (hydraulically speaking) shows appreciable levels of sensitivity to distance from the system inlet along both coordinate axes: parallel and normal to the mainline. However, as one moves further away from the inlet in a direction normal to the laterals, the contours tend to be parallel to the mainline. The implication is that in the lower half of the field sprinkler pressure head shows little variation with distance in a direction normal to the laterals, but exhibit appreciable sensitivity with distance in a direction parallel to the laterals. In addition, it can be noted that the pressure had contours within each of the field parcels show discernibly different curvature patterns as influenced by the changes in longitudinal field slope (Figure 15a). The contours in the region close to the upper boundary of each parcel tend to cluster more closely relative to the contours in the lower sections of, the same field parcel and, the parcel upstream. The implication is that within a field parcel, sprinkler pressure head decreases at a decreasing rate as one moves downstream along the laterals, but then the rate of decrease in sprinkler pressure head increases as one crosses into the field parcel downstream. Note that this is due to the interactive effects, of the field topographic configuration considered here and the decrease in discharge along a lateral, on the pressure head.

Figure 15b depicts the spatial distribution of sprinkler discharges. The maximum sprinkler discharge in the field is 0.1027L/s (1.628GPM) and it occurs at the inlet end of the sprinkler system. On the other hand, the minimum sprinkler discharge is 0.0996L/s (1.579GPM) and is located at the corner opposite to the inlet end of the field. The range of field-scale sprinkler discharge variation is 3.0% of the field-wide average discharge of 0.101L/s (1.6GPM). This represents a highly uniform field-scale spatial distribution of sprinkler discharges. In addition, if the irrigation application rates can be shown to be less than the soil steady state intake rate, this results should also imply a highly uniform irrigation; provided the system is properly installed, well maintained, and is operated under conditions of low wind speed. Note that the observations made in relation to the pattern of the sprinkler pressure head contours (Figure 15a) apply to the sprinkler discharge contours as well (Figure 15b). The lateral inlet discharges vary between a minimum of 4.123L/s (65.4GPM) and a maximum of 4.158L/s (65.9GPM). The total system discharge is 57.9L/s (917.0GPM) with the corresponding total dynamic head (specified at the input) being 158.0m.

Double-line laterals

The irrigated field considered in this example as well is rectangular in shape with a width of 160.0m and a length of 749.6m (Table 5, Figures 15c and 15d). The field has zero-cross slope. The length of the main is 160.0m and it runs across the middle of the field dividing the field into two equal halves of each 160.0m wide and 374.8m long (Figures 15c and 15d). The mainline here is comprised of pipe sections with the same diameter and hydraulic roughness characteristics as that used for the single-line laterals example presented above. It is installed on a surface with a constant elevation of 100.0m from the reference datum and has 15 equally spaced off-take nodes each supplying a pair of 374.8m long laterals installed on either side, resulting in total of 30 laterals in the field (15 on each side). On both sides of the mainline the laterals are set on a uniform slope of -0.055%. Each lateral consists of three segments of different diameter aluminum pipes (Table 5): over the upper 128.0m reach of a lateral 76.2mm diameter pipe sections were used, followed by a middle segment (spanning the distance between 128.0m and 228.0m from inlet end of the lateral) with a diameter of 63.5mm, and a distal segment (between 228.0m and 374.8ft) with a diameter of 50.8mm. Note that boundaries of the field parcels with different lateral diameters are shown by dashed lines in Figures 15a and 15d. Each lateral has 41 sprinklers installed at a regular spacing of 9.14m. The local head loss coefficients and the parameters of the sprinkler pressure head–discharge function are also given in Table 5.

The simulated spatial distribution of sprinkler pressure heads and discharges are summarized in Figures 15c and 15d, respectively. Noting that the two halves of the sprinkler system considered here represent two hydraulically parallel networks with the same geometric, hydraulic, and topographic characteristics (Table 5), subsequent discussion will focus on describing the pressure head and discharge distribution patterns for one-half of the field. The implication being the same inferences can be made for the other half of the field.

Considering either half of the field, it can be noted that the maximum sprinkler pressure head (56.1m) occurs at the system inlet and the minimum pressure head (48.8m) occurs at the field corner opposite to the inlet. The range of the field-scale sprinkler pressure head variation is 14.5% of the average pressure head (51.2m). This represents a sprinkler system operating at a much lower level of irrigation uniformity than that envisaged for the single-line lateral example presented above. It, nonetheless, represents a system with a field-scale sprinkler pressure head variation that is well within the recommended range for acceptable level of uniformity. Referring to the direction normal to the laterals in Figure 15c, the sprinkler pressure head distribution over the upper half of the field (hydraulically speaking) shows appreciable levels of sensitivity to distance from the sprinkler system inlet along both coordinate axes: parallel and normal to the main. On the other hand, in the lower half of the field, pressure head exhibits significantly reduced or little variability with distance measured from the system inlet in direction parallel to the mainline. However, sprinkler pressure heads shows appreciable levels of sensitivity to distance in a direction parallel to the laterals.

Considering either half of the irrigated field, the pressure had contours in each of the field parcels (field subdivisions with different lateral diameters) show discernibly different curvature pattern as influenced by the changes in lateral diameters (Figure 15c). Here as well, as in the single-line lateral example, the contours in the upper end of each field parcel tend to cluster more closely relative to the contours in the lower sections of, the same field parcel and, the parcel upstream. The implication being that within a parcel sprinkler pressure heads decrease with distance at a decreasing rate along the laterals, but then the rate of decrease in sprinkler pressure head increases as one crosses into the upper reach of the field parcel downstream (Figure 15c). Note that this is due to the interactive effects, of the lateral diameter configuration considered here and the decrease in discharge along a lateral, on the pressure head.

Figure 15d depicts the spatial distribution of sprinkler discharges with a maximum value of 0.1017L/s (1.612GPM) which occurs at the inlet end of the sprinkler system and a minimum value of 0.0945L/s (1.498GPM) at the corner opposite to the inlet. The range of field-scale sprinkler discharge variation is 7.5% of the field-wide average discharge of 0.0969L/s (1.536GPM). This represents a highly uniform spatial distribution of sprinkler discharges, which could lead to a highly uniform irrigation if the system is properly maintained and well managed. Note that the observations made in relation to the pattern of the sprinkler pressure head contours apply to the sprinkle discharge contours as well (Figure 15d). The lateral inlet discharges vary between 3.93L/s (62.3GPM) and 4.09L/s (64.8GPM). The system discharge is 119.2L/s (1889.1GPM) with a total dynamic head of 158.0m, which is specified at the input (Table 5). The system discharge is equally divided between the two halves of the irrigated field, this is due to the fact that the hydraulic, geometric, and topographic characteristics of the two subsystems are identical.

System hydraulic characteristics curves

Figure 15e depicts the functional relationship between total dynamic head and system discharge (system hydraulic characteristics) for both the single-line laterals and the double-line laterals layout configuration examples described above. While noting that the two sprinkler systems represent hydraulically different networks, some comparison of the system hydraulic characteristics can be made. Both curves show that the total dynamic head is a strictly increasing convex function of system discharge, which is in agreement with the general behavior of such a curve. The curve for the system with single-line laterals layout configuration has a steeper slope compared to that of the double-line laterals layout configuration. Considering the region of the system hydraulic characteristic curves where there is overlap, the preceding observation implies that for a given system discharge, the corresponding total dynamic head for the single-line laterals system would be much large than the total dynamic head for the double-line laterals system. In practical terms what this result suggests is that the pumps appropriate for operating these systems efficiently would have significantly different characteristics curves. In comparative terms it can be noted that high capacity, low head pumps would be more appropriate for the double-line laterals system and the opposite is true for the single-line laterals system.

Chapter 6. Summary and recommendations

Furrows have been the primary method of water application to vegetable crops in the Yuma Valley. However, solid set sprinkler irrigation systems are increasingly used for season long vegetable production. The installation cost of such systems can be high compared to surface irrigation systems; but sprinkler systems can attain high levels of application efficiencies and are amenable to automation, hence labor cost can be reduced significantly. When sprinkler systems are used for season long crop production, irrigation performance (uniformity and efficiency) is an important design and management criteria. Hence, in this project the performance of sprinkler systems designed primarily for supplementary irrigation purposes are evaluated, in light of the requirements of season long operation, through field and modeling studies. Here irrigation performance is evaluated in terms of irrigation application uniformity.

Sprinkler irrigation system field evaluations were conducted in growers' fields, in the Yuma Valley Irrigation Districts, where solid set sprinkler systems are used for season long vegetable crop production. The sprinkler systems used in the field evaluation have single-line laterals field layout configuration. The aim of the field evaluation was to evaluate field-scale irrigation application uniformities. In order to sample the effects of spatially variable factors on field-scale irrigation uniformity, during each field evaluation three test-plots, distributed over the irrigated field, were set up. Plot-scale irrigation uniformity (defined in terms of Christiansen's uniformity coefficient, UCC, and the low-quarter distribution uniformity, DU_{lq}) is computed based on precipitation data collected in the individual rain gages within a test plot. The plot-scale irrigation uniformities are then scaled up to field level through averaging.

As part of the study reported here, five additional field irrigation uniformity evaluations were conducted in the research farm of the Maricopa Agricultural Center of the University of Arizona. The same approach was used in the Maricopa field study as that of the Yuma Valley. In addition to the distribution uniformity data, in the Maricopa field study, hydraulic (pressure head and discharge) data were collected along selected laterals. The layout of the sprinkler system used in the Maricopa field evaluation has a double-line lateral field layout configuration and the hydraulic data collected in the study was used to evaluate the hydraulic model developed as part of the study.

Test-plot scale UCC and DU_{lq} values computed for the first field evaluation in the Yuma Valley Irrigation District range between 0.58 and 0.89 and between 0.48 and 0.84, respectively. The field-scale average UCC is 0.75 and DU_{lq} is 0.69. For the second test the computed UCC ranges between 0.87 and 0.91 and DU_{lq} vary between 0.84 and 0.88, with a field-scale average UCC of 0.90 and DUlq of 0.85. The results suggest that the field-scale irrigation uniformity for these farms can be described as moderately high to high. The implication is that water availability would not be a constraint to obtaining a uniformly high crop yield over the irrigated field, provided the irrigation duration is set such that adequate depth is applied during each irrigation event and that the application rate is sufficiently small to prevent surface accumulation of irrigation water. The acceptably high field-scale application uniformity is a function of two important factors: (1) low average wind speed (≤1.8m/s) which resulted in minimal wind drift and distortion in the application pattern of irrigation water around a sprinkler and (2) a sprinkler system hydraulics characterized by minimal energy loss, and hence a highly uniform sprinkler pressure head and discharge distribution.

The results of the field irrigation uniformity evaluations conducted in the Maricopa Agricultural Center show a high test-plot scale UCC (ranging between 0.75-0.92) and DUlq (varying between 0.69-0.88). The field-scale averages were a UCC value of 0.86 and a DU_{lq} value of 0.78. The wind speed during the irrigation evaluation was low (≤2.5m/s), which is conducive to the attainment of higher irrigation uniformity. The high field-scale irrigation uniformity maintained over a series of irrigation events in the Maricopa study can be explained by the fact that the sprinkler system, described here, was specifically set up for research purpose and that care was exercised in ensuring proper installation and operation of the system. Considering this and the fact that the sprinkler system used in the study is relatively smaller in size compared to a typical field sprinkler system in the Yuma Valley Irrigation District; the irrigation uniformity results obtained in the Maricopa study are significant only to the extent that a sprinkler system with sufficiently large lateral and mainline diameter (typical of sprinkler systems in the Yuma area) can attain high levels of irrigation uniformity provided the system is well maintained and is operated under low wind speed conditions. The results described above are in agreement with results of earlier sprinkler irrigation field studies conducted by the authors in the Yuma Valley Irrigation District (Zerihun et al., 2011).

As part of the current study a mathematical model is developed for the hydraulic analysis of field-scale solid set sprinkler system. The model has the capability to conduct hydraulic characterization, simulation, and design computation of sprinkler systems with both single-line and double-line laterals layout configuration. The sprinkler system can have spatially variable hydraulic, geometric, and topographic attributes. The component of the mathematical model, designed for the hydraulic analysis of sprinkler systems with single-line laterals field layout configuration, was developed and evaluated with field data as part of a previous study. The results of the study showed that model predictions compare well with field data, suggesting that the numerical algorithms of the hydraulic model are accurate. However, the component of the numerical algorithm designed for hydraulic analysis of sprinkler systems with double-line laterals field layout configuration was developed as part of the current study. A limited evaluation of the model was conducted through comparison with field data. The results of model evaluation show that measured and computed pressure heads differ by a maximum of 3.3% of the measured pressure heads along the laterals, the average error being 1.5%. Along the main the maximum error in model predicted pressure head is 11.6% of the measured values and the average error is 2.0%. Error in model predicted lateral inlet discharges vary between 9.9-14.9% with an average value of 11.8%. The results suggest that the numerical algorithms of the model are accurate. The relatively larger difference between the computed and measured lateral inlet discharges can be, to a significant extent, attributed to the low precision (10GPM) of the flow meter.

The hydraulic model developed here generates various types of output data, including: hydraulic characteristics curves for each mainline outlet and for the system inlet, energy and hydraulic grade lines along the main and each of the laterals, discharges at each of the computational nodes along the main and the laterals, and sprinkler pressure heads and discharges (Zerihun and Sanchez, 2012). However, in subsequent discussion only a brief summary of the model outputs that have direct significance from irrigation management perspective are presented: the field-scale spatial distribution of sprinkler pressure heads and discharges.

The hydraulic model was used to evaluate the spatial distribution of the sprinkler pressure heads and discharges of the field-scale sprinkler system used in the Maricopa study. The simulated field-scale sprinkler pressure heads and discharges vary within

3.5% and 1.7% of the field-wide average pressure heads and discharges, respectively. Note that the narrow range of the computed sprinkler pressure head and discharge is consistent with the highly uniform pressure heads measured along the laterals: the ranges of measured pressure head along the laterals vary between 2.7% and 5.2% of the average lateral pressures. Both the computed and measured pressure head variations are well within the maximum recommended range for sprinkler system design. The sprinkler system used in this study is experimental (hence properly set and operated) and is relatively smaller than a typical field-scale sprinkler system in the Yuma Valley Irrigation Districts. However, these results suggest a potentially high application uniformity over the irrigated field for well maintained and operated sprinkler irrigation systems in the Yuma Valley. Furthermore, with the aim of highlighting the capabilities of the model, results of simulation of the field-scale distribution of sprinkler pressure heads and discharges for systems with spatially variable geometric (lateral diameter) and topographic (lateral slope) attributes are presented.

A one-dimensional sensitivity analysis was conducted to establish the relative significance of the effects of total dynamic head, lateral diameter, field slope along laterals, and pipe absolute roughness on the spatial distribution of sprinkler pressure heads and discharges of the sprinkler system used in the Maricopa study. The result shows that changes in the total dynamic head at the mainline inlet (within a reasonable range) have no appreciable effect on the field-scale distribution pattern of the sprinkler pressure heads and discharges and their ranges of variation. However, changes in total dynamic head have a significant affect on the actual values of pressure heads and discharges. The result suggest that keeping all other factors constant, sprinkler pressure heads and discharges are increasing functions of total dynamic head. This highlights the importance of maintaining the accuracy of the pressure gage and/or flow meter of the pump. These results are entirely consistent with the results that have been obtained for a field-scale sprinkler system with single-line laterals layout configuration in an earlier study in the Yuma Valley Irrigation District.

The results of the modeling study also show that the ranges of variations and the spatial distribution patterns of sprinkler pressure heads and discharges are highly sensitive to changes in lateral diameter. The hydraulic characteristics of the sprinkler system show slight sensitivity to small changes in field slope. On the other hand, a relatively large, but reasonable increase in field slope can lead to appreciable changes in spatial distribution patterns of the sprinkler pressure heads and discharges and locations of the minimum pressure heads and discharges. However, the ranges of variations in field-scale sprinkler pressure heads and discharges are not affected in a significant way. In addition, the results show that the hydraulics of the sprinkler system in the test farm is virtually insensitive to significant changes in pipe absolute roughness. The high sprinkler pressure head and discharge uniformity and the low sensitivity of the sprinkler system hydraulics to changes in pipe absolute roughness have been shown to be directly related to the fact that system hydraulics is dominated by the relatively large diameters of the lateral and the mainline. The effect of pipe diameter compared to slope and hydraulic roughness characteristics of the pipe can be readily evident by examining the energy equation, which shows that pipe diameter has a strong nonlinear effect on the energy equation compared to the linear effect of land surface slope and a much milder nonlinear effect of pipe absolute roughness. Although large pipe diameters have the added advantage of reducing system running cost; they might, however, lead to increased installation costs of the system.

Overall, the results of field-scale hydraulic modeling studies (current and past) suggest that typically the hydraulic design of sprinkler system in the Yuma Valley is robust. The practical effect of which is that if a typical field-scale sprinkler system in the Yuma area is properly set, well maintained, and operated under conducive ambient weather conditions, it can produce high levels of irrigation uniformity under widely varying field slopes and hydraulic roughness. The results of field irrigation uniformity studies (current and previous) also support the preceding observation: field-scale sprinkler irrigation uniformities can be maintained at a high level (a UCC of about 0.8), provided the system is operated at relatively low average wind speed (about or less than 2.0m/s), irrigation does not take place under hot and dry weather conditions, attention is given to proper regular maintenance of the sprinkler system (frequent inspection and maintenance of system components especially sprinklers), and application rate is low enough to prevent runoff.

The following set of recommendations identifies the limitations of the current study and outlines possible challenges for further studies aimed at improving sprinkler irrigation system design and management in the Yuma Valley Irrigation District:

1. Field-scale sprinkler irrigation uniformity is a function of various factors (weather, system hydraulics, level of system maintenance, and irrigation management) that may possibly vary in time and space. Considering the limited nature of these studies, the results cannot be generalized with high degree of certainty for the entire Yuma Valley Irrigation District. Hence, additional field studies may need to be conducted, in order to establish typical irrigation uniformity levels, and the range of variation, across the irrigation district.
2. Irrigation uniformity defines one aspect of irrigation performance, the others being field application efficiency and irrigation adequacy. Irrigation uniformity is often used to characterize sprinkler system performance, because the factors used to compute uniformity are relatively easy and inexpensive to measure and that there are standardized field methods for collecting the requisite data. While high uniformity is a prerequisite for high application efficiency, high application efficiency does not automatically follow high uniformity. The duration of irrigation application must be set such that irrigation is adequate and efficient, considering irrigation interval, crop, soil, and atmospheric conditions.
3. Optimal design and management of field-scale sprinkler systems is key to the efficient irrigation of crops with such systems. Mathematical models are inexpensive and flexible tools for the design and management of sprinkler systems. A mathematical model capable of quantifying field-scale sprinkler irrigation performance (uniformity, efficiency, and adequacy) as a function of hydraulic, geometric, topographic, soil, atmospheric, and crop factors requires the coupling of a rigorous field-scale sprinkler hydraulic model (e.g., Zerihun and Sanchez, 2011, Zerihun and Sanchez, 2012) with a droplet-dynamics submodule (for computing the pattern of precipitation around a sprinkler, e.g., Playan et al., 2009) and a soil water flow model (for simulating subsequent infiltration and soil water flow processes, e.g., Simunek et al., 2009). The development of a computationally efficient and robust coupled field-scale sprinkler model for system design and management applications remains a challenge.
4. A sprinkler system with high irrigation application uniformity may not necessarily be optimal from economic cost/benefit perspective. Hence, a more comprehensive field-

scale sprinkler system evaluation may include economic evaluation of existing and alternative system layouts, pipe sizes, pipe appurtenances, and sprinkler combinations.

5. Field experience suggest that attention needs to be given to the proper setting and routine maintenance of the sprinkler system in order to realize potentially achievable field-scale sprinkler irrigation uniformities. Some of the issues that require consideration in this regard are: proper setting of laterals such that sprinkler risers are vertical, routine maintenance of system components (particularly cleaning of sprinklers following or prior to an irrigation event), timely replacement of worn out sprinklers and damaged pipe sections, and need to guard against inadvertent mixing of sprinklers with different hydraulic characteristics.
6. Experience with field studies suggest that for field-scale sprinkler systems that are well maintained, a single test-plot placed somewhere in the middle of the field can provide precipitation data that can adequately characterize field-scale uniformity. However, if possible two or three test-plots distributed uniformly (preferably along the field diagonal from the sprinkler system inlet), unless other requirements dictate otherwise, can be used to obtain a more representative sample of the variations in field-scale irrigation uniformity.

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