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Hydraulics of Linear-move Sprinkler Irrigation Systems, I. System Description, Assumptions, and Definition of the Hydraulic Simulation Problem

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Abstract

This manuscript is the first of a three-part paper that presents the development and evaluation of a numerical hydraulic model for linear-move sprinkler irrigation systems equipped with pressure reducing valves (*prvs*). Discussions on model development and evaluation are presented in part-two and three of the article, respectively. The current manuscript, on the other hand, focusses on system description, statement of pertinent model assumptions, and the definition of the lateral hydraulic simulation problem and as such it is intended to set the background for the discussions that follow in the companion manuscripts. A concise description of the configuration of the linear-move sprinkler irrigation system, considered in the current study, and its components is presented here. In addition, system attributes that are of particular relevance to hydraulic modeling of linear-move laterals are discussed. Noting that pressure reducing valves are key to achieving a controlled application of irrigation in linear-move systems, the full range of the operating modes of *prvs* are defined, in the context of irrigation laterals, and their effects on system hydraulics are described. In addition, assumptions that form the basis of the lateral hydraulic simulation model, presented in the companion manuscript, are stated here. Finally, the lateral hydraulic simulation problem is defined and the linear-move lateral is schematized as a branched pipe network, consisting of links and nodes, for hydraulic analysis and simulation.

Keywords: Linear-move; *prvs*; Manifold; *prv* operating modes

Notations

h_{min}: Minimum required *prv*-inlet pressure for the *prv* to function reliably in the active mode *[L]*;

h_{max}: Maximum recommended *prv*-inlet pressure for the *prv* to operate reliably in the active mode *[L]*;

h_{prv}: *prv*-set pressure *[L]*;

h_u: *prv*-inlet (-upstream) Pressure *[L]*;

δh_{prv}: Minimum recommended pressure head margin between h_u and h_{prv} for the *prv* to function reliably *[L]*;

prv: Pressure reducing valve *[-]*.

Introduction

Linear-move sprinkler irrigation systems are used to irrigate a range of crops [1] at high levels of application efficiency [2]. The availability of accurate and flexible mathematical models can contribute to improved hydraulic analysis, design, and management of these systems. Studies on the hydraulic analysis and design of continuous-move systems, including linear-move systems, were conducted by various authors [3-10]. The models proposed in these studies have limitations in terms of their ability to account for span geometry and *prv* effects on lateral hydraulics.

The objective of the study, presented in the current paper, is the development and evaluation of a hydraulic simulation model for linear-move sprinkler irrigation systems equipped with pressure reducing valves, *prvs*. This manuscript is the first of a three-part article. Part-two of the paper describes the formulation and numerical solution of the lateral hydraulic simulation problem. The third manuscript presents results of model evaluation and explores potential applications of the model. The focus of this manuscript, on the other hand, is the description of system components, statement of model assumptions, and definition of the lateral hydraulic simulation problem and as such it is intended to set the background for the discussions that follow in the companion manuscripts.

A concise description of the linear-move sprinkler irrigation system configuration, considered in the current study, and key system components is presented here. System attributes that are of particular significance in the hydraulic modeling of such a system are discussed. Accordingly, a linear-move lateral is considered here as a concatenated series of arched spans with known geometry and multiple outlet ports. Low-pressure sprinklers or spray nozzles are used to distribute irrigation water along the lateral. Each sprinkler is coupled to a *prv* at its inlet-end and water is conveyed from a lateral outlet-port down to the *prv*-sprinkler assembly through a drop-tube. *prvs* are pressure regulating devices, placed upstream of each sprinkler, and are designed to maintain a set pressure at the sprinkler inlet regardless of the pressure upstream of the *prv*, provided the upstream pressure varies within a recommended range [11]. In a well-designed and maintained system, the use of a *prv*-sprinkler assembly as an emission device should lead to a uniform and efficient application of water and hence agricultural chemicals along the lateral.

Depending on their modes of operation, pressure reducing valves can have a significant effect on the hydraulics of a lateral. Accordingly, the full range of operating modes of *prvs* are defined, and their effects on system hydraulics are described, here in the context of an irrigation lateral. In addition, key assumptions that form the basis of the linear-move lateral hydraulic simulation model presented in manuscript II are stated here. Finally, the lateral hydraulic simulation problem is defined

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and the linear-move sprinkler irrigation lateral is schematized as a branched pipe network, comprised of links and nodes, for hydraulic analysis and simulation.

System Description

A linear-move sprinkler irrigation system is a self-propelled machine consisting of steel or aluminum lateral that applies water to crops in the form of precipitation, as it moves across a rectangular field. A linear-move lateral is placed at a suitable above ground clearance atop an elevated platform consisting of structural elements, drive units, and alignment and guidance mechanisms that support and propel the system as well as keep it aligned and on course along its travel direction during irrigation. A sketch of a typical linear-move lateral obtaining its supply from a canal - with an intake apparatus, a pump, and a power unit attached to its inlet-end - is depicted in Figure 1a. The lateral is comprised of a series of arched spans connected, at their lowest points, with joints that allow relative movement between adjoining spans. Each span has multiple regularly or variably spaced outlet ports.

Often semi-flexible tubing, referred to as drop-tubes, is used to convey water from a lateral outlet port down to a sprinkler (Figure 1b). A curved rigid tubing, called gooseneck connector, is used to connect each outlet port on the lateral with a drop-tube. The drop-tubes in linear-move systems are often fitted with pressure reducing valves, *prvs*. Some linear-move systems have *prvs* installed at the inlet-end of the drop-tube. Other systems have *prvs* placed at the lower end of the drop-tube, just upstream of the sprinklers, and the *prv*-sprinkler assembly is then suspended from the lateral at a suitable above ground clearance [11]. The sprinklers, typically used, in these systems are low-pressure sprinklers and are often combined with accessories known as deflector pads to produce a range of precipitation patterns that may

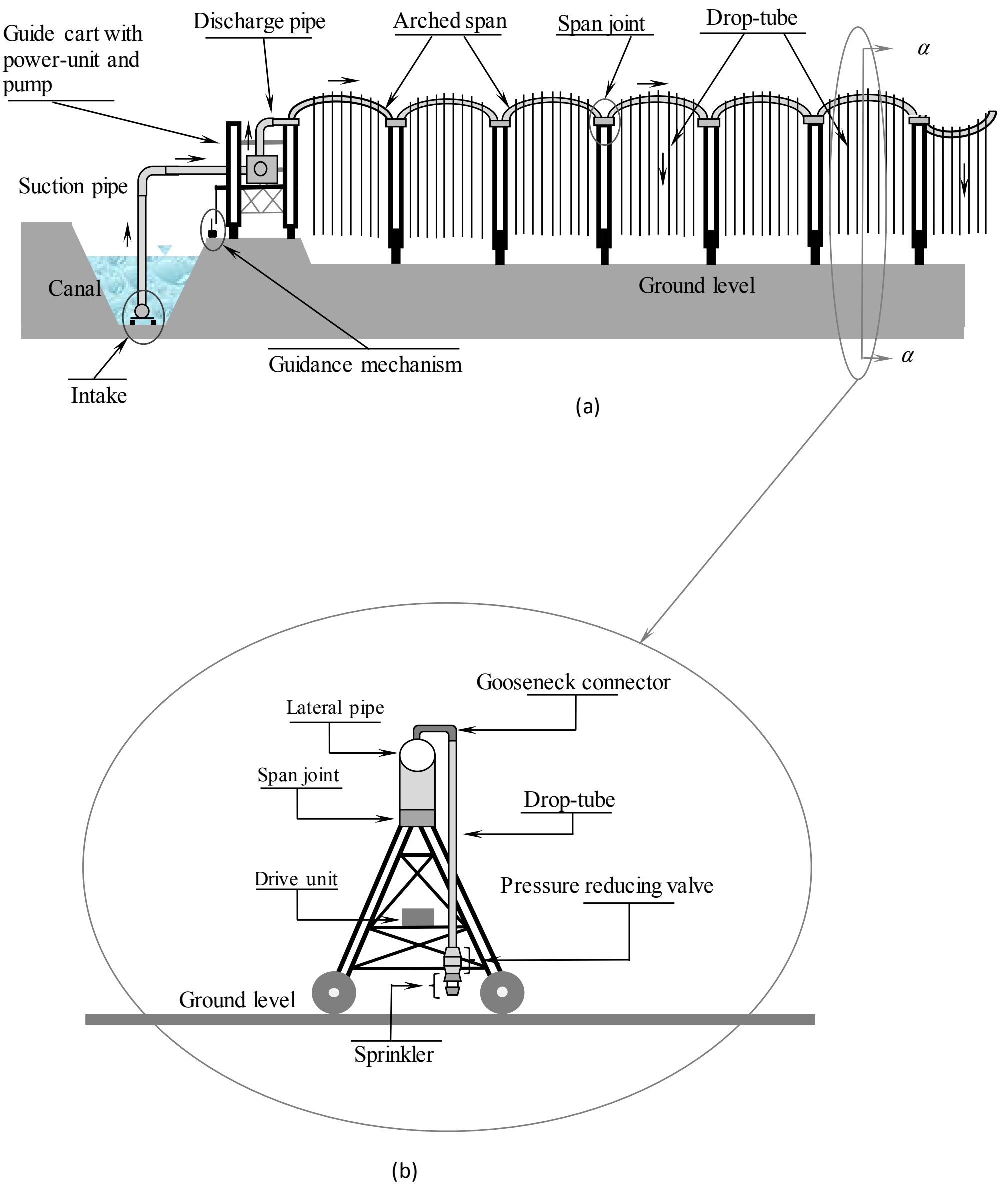

Figure 1: (a) Sketch of a linear-move system obtaining its water supply form a canal and (b) section at α-α, showing details of a support tower and drop-tube fitted with a *prv*-sprinkler assembly.

suit different applications. The combined use of *prvs*, which allows precise control of sprinkler discharges, and low-pressure sprinklers in linear-move systems, can result in increased irrigation uniformity and efficiency.

From the perspective of hydraulic modeling, the pipeline that conveys water across a linear-move machine is essentially an irrigation lateral and will be treated as such herein as well as in the companion manuscripts where model development and evaluation are described. Nonetheless, a linear-move lateral differs from the conventional irrigation laterals of solid-set or set-move systems in the following respects: it moves across the field as it applies irrigation water, it is comprised of arched spans placed on an elevated platform, sprinklers are often suspended from the lateral at a suitable above ground clearance, and many linear-move laterals are fitted with pressure reducing valves upstream of the sprinklers. A set of assumptions that form the basis of the model developed in the current study, including those that relate to the effects of lateral movement and span curvature, will now be presented. Before that, however, description of *prvs*, *prv* operating modes, and their effects on lateral hydraulics will presented.

Pressure Reducing Valves and Their Effects on Lateral Hydraulics

Pressure reducing valves, *prvs*, are key to achieving a controlled application of irrigation along a linear-move lateral. *prv* effects on lateral hydraulics and their ability to regulate pressure depends on their modes of operations. Thus, the full range of the operating modes of *prvs* are defined, in the context of irrigation laterals, and their effects on system hydraulics are described here. Considerations of pressure regulation accuracy of *prvs* and their implications on lateral hydraulic modeling are also highlighted.

Description of pressure reducing valves

Pressure reducing valves are used in hydraulic networks to maintain a constant set pressure, at a suitably selected downstream node, regardless of the pressure upstream [12-16]. For field-scale sprinkler irrigation applications, which is the focus of the current study, the network node where pressure is to be regulated is the downstream or outlet end of the *prv*. Furthermore, in these systems the pressure setting of the *prv* is generally programmed into the device by applying a specific stress to a spring that actuates valve movement in the *prv* [11].

Given a set pressure, a pressure reducing valve in an irrigation lateral regulates its outlet pressure using a mechanism that varies the in-device head loss (i.e., the energy loss within the *prv*) in accordance with the changes in its inlet pressure. Changes in the inlet pressure of a *prv* would automatically be felt at its outlet. Deviations in the outlet pressure, from the set pressure, initiate the movement of a spring-loaded valve within the *prv*, leading to adjustments in the size of an aperture through which water passes and hence to variations in *prv* head losses [11]. Overall, outlet pressures exceeding the set pressure cause the valve to close and the head losses to increase. The converse is true when outlet pressures fall below the set pressure. Thus, a balance between the force acting on the spring actuating the valve element and the spring resistance establishes the set pressure at the *prv*-outlet and determines the corresponding position of the valve element.

Pressure reducing valves are designed to regulate downstream pressure when the inlet pressure varies within a (manufacturer) recommended range. However, if a *prv* is operated under inlet pressures that fall outside the recommend range, the valve can be in its fully open or fully closed position (or nearly so). In which case, the *prv* will not function as a pressure regulator and it will have a distinctly different effect on the hydraulics of the system. Accordingly, when *prvs* are present in a hydraulic network, the network topology and pertinent equations describing flow vary depending on the operational modes of the *prvs* [12-14,17]. Thus, defining the modes of operations of *prvs* and description of their implications in system hydraulics are integral to the simulation and analysis of the effects of *prvs* on hydraulic networks.

Modes of operations of *prvs* for the purpose of hydraulic modeling of irrigation laterals

The criteria used here to characterize the operational modes of *prvs* draws broadly on the approach developed for modeling and analyses of water distribution networks [12-14,17] while taking into account the particulars of the hydraulics of linear-move laterals. Accordingly, for *prvs* installed in irrigation laterals three distinct operational modes can be discerned: *(i)* Active mode, *(ii)* Passive mode, and *(iii)* Fully-throttled mode. An additional operational mode can be defined for large water distribution networks with complex topologies; however, these operational modes cover the entire range pertinent to *prvs* on linear-move laterals. The following is a description of the *prv* operational modes enumerated here.

(i) Active mode: A pressure reducing valve is said to operate in the active mode, if it can maintain a constant set pressure at its outlet when it is subjected to an inlet pressure that equals or exceeds the manufacturer recommended minimum pressure. From practical computational perspective, however, a functioning *prv* is considered here to operate in the active mode when its upstream or inlet pressure head, h_u *[L]*, is within a pressure range recommended by the manufacturer

$$h_{\min} \le h_u \le h_{\max} \tag{1}$$

In eqn. (1), h_{min} and h_{max} are the lower and upper limits, respectively, of the recommended *prv*-inlet pressure head range for the *prv* to operate reliably in the active mode *[L]*. Specifications of *prvs* provided by manufacturers often include h_{max} or the range over which it varies, but may not specifically state h_{min} [11,18,19]. However, manufacturers also provide the *prv*-set pressure, h_{prv} *[L]*, and the minimum required margin between h_u and h_{prv} for the *prv* to operate reliably in the active mode, δh_{prv} [11]. Thus, the corresponding h_{min} can be calculated as the sum of h_{prv} and δh_{prv}.

$$h_{\min}=h_{prv}+\delta h_{prv} \tag{2}$$

In practical terms, the requirement stated in eqn. (1) implies that if a *prv*-inlet pressure, h_u, varies in the interval $h_{min} \le h_u \le h_{max}$, then the margin between h_u and the *prv*-set pressure, h_{prv}, is at least equal to the minimum head differential that the *prv* requires in order to actively regulate downstream pressure and is at most equal to the maximum head that the *prv* is designed to dissipate so as to produce a reduced outlet pressure sufficiently close to the set pressure. Under such a scenario, the control valve would be somewhere in between the fully open and fully throttled positions and as such it can adjust its position, and hence the valve aperture size, in accordance with the changes in the *prv*-inlet pressure in order to control the downstream pressure.

(ii) Passive mode: A pressure reducing valve is said to operate in the passive mode, when the inlet pressure head, h_u, is less than the minimum required for the *prv* to operate reliably in the active mode, h_{min}, thus

$$h_u<h_{min} \tag{3}$$

The minimum required pressure head margin for an active *prv*, δh_{prv}, accounts for the head loss in a fully open *prv* plus perhaps a safety margin. However, for convenience δh_{prv} is treated here as the typical head loss in a fully open *prv*. Thus, it can be readily shown based on eqn. (2) that when the *prv*-inlet pressure head is less than the recommended minimum, eqn. (3), then the margin between h_u and h_{prv} would be less than δh_{prv}. The implication is that for the case in which $h_u < h_{min}$ there will not be sufficient head at the *prv*-inlet to maintain the constant set pressure at the outlet and hence pressure at the outlet will be less than the set pressure. Under such a scenario, the control valve would be in its fully open position, beyond which no further increase in aperture size is possible. Thus, the *prv* will no longer function as a pressure regulator, instead it becomes a passive network element.

(iii) Fully throttled mode: A pressure reducing valve is considered here to operate in a fully throttled mode if the *prv*-inlet pressure, h_u, exceeds the maximum recommended inlet pressure, h_{max}, thus

$$h_{max} < h_u \tag{4}$$

Overall, when the *prv*-inlet pressure exceeds a certain threshold, which may vary depending on the model and size of the *prv*, it is conceivable that the control valve would be in its fully closed position or it would have reached a set minimum aperture size. Note that a similar scenario is described by Giustolisi et al. [16] in the *prvs* considered in their studies. In theory, h_{max} in eqn. (4) can be considered as such a threshold pressure. In which case, for *prvs* operating in the pressure range $h_{max} < h_u$, the margin between the *prv*-inlet pressure head and the *prv*-set pressure exceeds the maximum head that can be dissipated in the *prv* to produce the constant set-pressure at the outlet. Under such a scenario, the control valve would be in its fully closed position and hence the attached sprinkler will not be functional. Alternatively, the valve opening may have reached a set minimum and hence the outlet pressure cannot be reduced to the set pressure.

In practice, however, the maximum (manufacturer) recommended inlet pressure, h_{max}, for a proper functioning of the *prv* in the active mode could possibly be set less than the threshold described above by a safety margin. The implication is that in at least a fraction of the *prv*-inlet pressure range specified in eqn. (4), the *prv* may still be attempting to regulate pressure but is ineffective, thus the reduced outlet pressure may not be sufficiently close to the set pressure. The implication is that the *prv* should not be operated in this pressure range anyway. Thus, from practical computational perspective *prvs* operating under inlet pressure heads exceeding the manufacturer recommended h_{max} are treated here as fully throttled and hence the attached sprinkler is considered not functional.

Implications of the modes of operations of *prvs* on lateral hydraulics

In linear-move sprinkler systems, the function of the pressure reducing valves is to isolate individual sprinklers along the lateral from the direct effect of the system hydraulics upstream, and thereby maintain a suitably selected set pressure at the inlet of each sprinkler. From irrigation management perspective, the goal is to keep sprinkler discharges, along the lateral, sufficiently close to the recommended rate and in effect achieve high sprinkler discharge uniformity and possibly efficient and uniform irrigation and agricultural chemical application. However, the preceding shows that the inlet pressure of a sprinkler fitted with a *prv* can vary depending on the mode of operation of the *prv*.

For pressure reducing valves that are active, it can be observed that the pressure head at the sprinkler inlet, h_s, is independent of the system hydraulics upstream and is equal to the set pressure of the *prv*, h_{prv}:

$$h_s = h_{prv} \tag{5}$$

The implication is that for a *prv* operating in the active mode, the discharge of the attached sprinkler can be obtained directly from the sprinkler head-discharge characteristics, as a function of the *prvs* set pressure, without consideration of the system hydraulics upstream of the pressure reducing valve. By contrast, if the pressure reducing valve is operating in the passive mode, then the attached sprinkler is interacting directly with the system hydraulics upstream. Thus, for a passive *prv*, the discharge through the attached sprinkler can be computed following the same approach as that used in laterals without *prvs* [18,19]. The only exception here is that the local head loss introduced by the fully open pressure reducing valve needs to be considered. Finally, if the inlet pressure head of a *prv* exceeds the recommended maximum, then the pressure reducing valve is considered here to be fully throttled and hence the attached sprinkler is assumed not to be functional.

A more detailed discussion on the computational approaches used to account for the effects of the different operational modes of *prvs* on irrigation lateral hydraulics is presented in manuscript II.

Pressure regulation accuracy and practical considerations

The preceding shows that the set pressure of a *prv* is a key variable in modeling the effects of *prvs* on lateral hydraulics. It is the main determinant of the operational modes of a *prv* and represents the constant outlet pressure of the *prv* (or more importantly the constant inlet pressure of the attached sprinkler), when the *prv* is operating in the active mode. However, there is a point that needs to be addressed here as regards the accuracy of pressure regulation and its implication on the significance and practical meaning of the set pressure of *prvs*.

Pressure reducing valves are hydro-mechanical devices and hence it is conceivable that they operate under some specific accuracy limits. Generally, performance curves produced by *prv* manufacturers show that the accuracy of pressure regulation varies as a function of the hydraulic condition under which a *prv* is operating [20,21]. They also show that for a given set of hydraulic conditions, accuracy depends on the model and size of the *prv* as well. Furthermore, it is known that valve hysteresis can have some effect on the accuracy of pressure regulation [11,22]. These suggest that given an inlet pressure, the actual reduced pressure at the outlet of a *prv* may not necessarily exactly match the set pressure. This may imply an inconsistency in the notion adopted earlier that the *prv*-set pressure can be used as a characteristic variable in accounting for *prv* effects on system hydraulics. However, it is important to note here that the use of the set pressure of a *prv* as a characteristic variable presumes that, for the hydraulic conditions under which the *prv* is typically operated, the variation in the *prv*-outlet pressure about the set pressure is limited within a sufficiently narrow band. Thus, for practical computational purposes the *prv*-set pressure can be treated as a good approximation of the reduced outlet pressures of an active *prv*.

Accordingly, the operational assumption built into the model presented in the companion manuscript is that for a given application, the model and size of the *prvs* in a lateral are selected (at system design stage) such that the variation in the *prv*-outlet pressures would be maintained within some acceptable tolerance about the set pressure as the *prv*-inlet pressures vary (along the lateral) within the maximum expected range. Thus, for practical computational purposes the set pressure can be considered a sufficiently close approximation of the reduced outlet pressures of an active *prv*.

Assumptions and Definition of the Hydraulic Simulation Problem

The assumptions that form the basis of the linear-move lateral hydraulic simulation model, developed in the current study, are summarized here. This is followed by a definition of the hydraulic simulation problem, where a linear-move sprinkler irrigation lateral is schematized as a branched hydraulic network and specification of the lateral hydraulic simulation problem is stated.

Assumptions

The configuration and modes of operation of a linear-move lateral considered in the current development satisfy the following requirements: (1) A lateral has multiple segments connected in series (referred here as lateral pipe segments), each delimited at least at one of its ends by an outlet port and at the other by the inlet-end of the lateral or a span joint. Typically, however, a lateral pipe segment is delimited at both ends by an outlet port. (2) A lateral pipe segment is characterized by its slope, diameter, hydraulic resistance parameter, and length. (3) The parameters of lateral pipe segments as well as the hydraulic characteristics of sprinklers can vary along a lateral. (4) A lateral does not contain inline devices that add energy into the system, but pipe appurtenances such as valves and fittings and bends can be placed anywhere along the lateral. (5) The lengths of the lateral pipe segments and drop-tubes are sufficiently large for the flow within these network elements to be considered fully developed and hence the uniform flow friction head loss equations can be applied to calculate energy loss within them. (6) Lateral flow velocities, the curvature of the arched spans, and the length of the lateral pipe segments are sufficiently small for pipe curvature effects on the hydraulic resistance of the lateral pipe to be considered negligible. (7) The travel speeds of linear-move machines are sufficiently small for the dynamic effects of lateral movement on its hydraulics to be considered negligible. (8) Each drop-tube along a lateral is fitted with a *prv*-sprinkler assembly at its downstream end. And (9) The model, size, set-pressure, and other parameters of the *prvs* installed in a given lateral are the same.

Definition of the lateral hydraulic simulation problem

Linear-move lateral as a branched hydraulic network: For the purpose of hydraulic modeling, a linear-move lateral is treated here as a branched pipe network consisting of hydraulic links and nodes (Figure 2a). A lateral pipe segment or a drop-tube fitted with a *prv*-sprinkler assembly is considered as a hydraulic link and the link discharges are system unknowns.

The nodes consist of fixed head nodes and junction nodes. The fixed head nodes are boundary nodes and include the lateral inlet and the exit ends of each sprinkler. These nodes either have a known total head or have total heads that can be defined in terms of the discharge and elevation of individual sprinklers, thus they do not need to be specifically treated as unknowns of the hydraulic simulation problem. Junction nodes are points along the lateral at which two or more links are joined (Figure 2b and 2c). These include span joints (non-offtake nodes) and nodes where drop-tubes connect to lateral outlet ports (offtake nodes). The total heads at each of the junction nodes are system unknowns and need to be determined as part of the hydraulic computation. Note that span joints are treated here as junction nodes so as to allow a more accurate representation of the effect of lateral elevation on the pressure head profile of a linear-move lateral. As can be observed from Figure 2c, for computational convenience it is assumed here that a junction

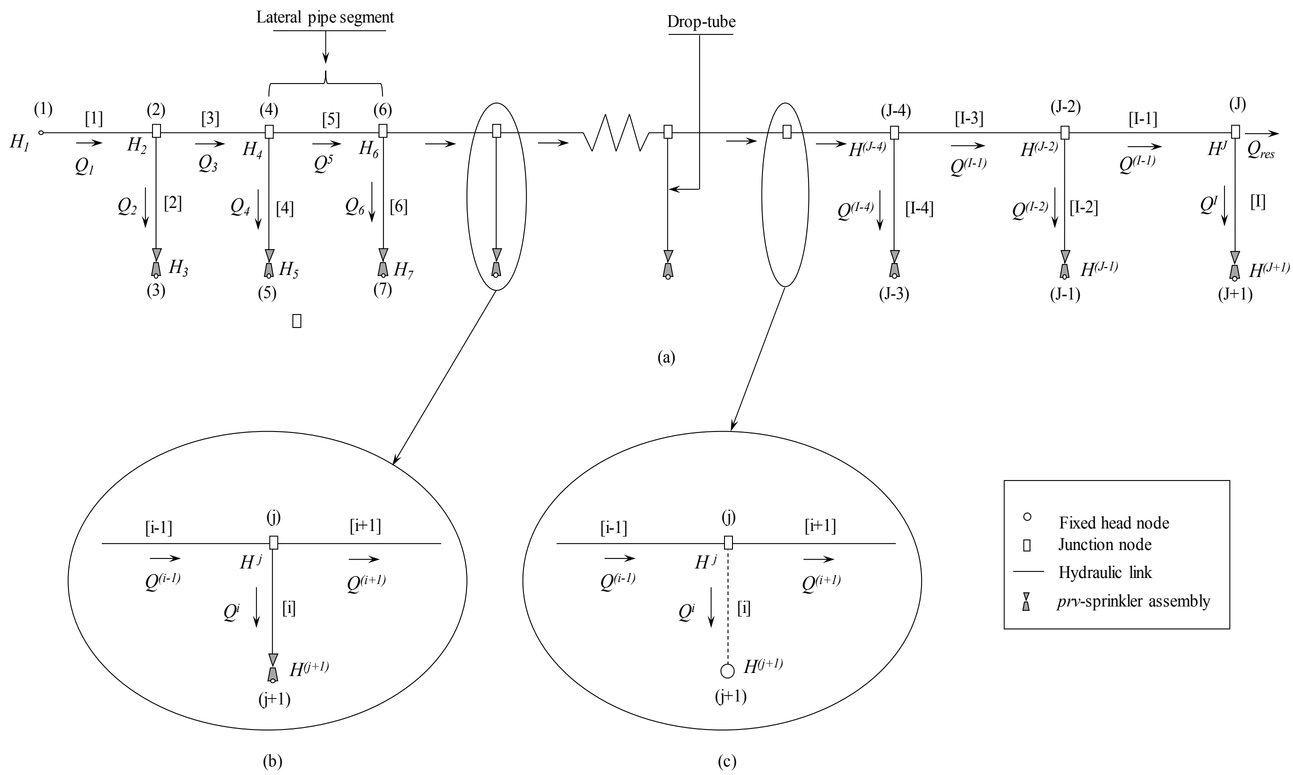

Figure 2: (a) Schematics of a linear-move lateral as series of links delimited by nodes. (b) An offtake junction node and attached links, and (c) a non-offtake junction node (i.e., a node without a drop-tube) and attached links. (Note: for computational convenience, it is assumed here that a virtual drop-tube with zero discharge is connected to each non-offtake junction node. Notations: (*i*) is node index, [*j*] is link index).

node representing a non-offtake point along the lateral, such as a span joint, has a virtual link with zero discharge attached to it. Note that with this convention, each of the odd nodal indices represents a fixed head node and all even indices represent junction nodes. Furthermore, all of the odd link indices represent lateral pipe segments and each of the even indices represents a drop-tube with a *prv*-sprinkler assembly or a virtual link in the form of a drop-tube with zero discharge.

Specification of the lateral hydraulic simulation problem: The problem of interest here is hydraulic simulation of a linear-move lateral equipped with pressure reducing valves and is operated under steady flow condition. Thus, the modeling objective is to determine all the link discharges and the unknown nodal heads (heads at junction nodes), given the slope, geometric, and hydraulic characteristics of the lateral, including the total head at the inlet. Forms of the energy conservation and continuity equations [23], applicable to steady incompressible flow in stationary and straight pipelines, can be used to model the hydraulics of such a lateral. Accordingly, a continuity equation can be written for each junction node and an energy balance equation can be formulated across each link. For a general lateral hydraulic simulation problem, these equations can be coupled to form a system of nonlinear equations that can be solved iteratively [24]. However, as a first approximation the relatively simpler, nonetheless accurate, manifold approach is used in the formulation and numerical solution of the hydraulic simulation problem of linear-move systems with *prvs*.

Discussion and Conclusion

This manuscript is the first of a three-part article on the development and evaluation of a hydraulic simulation model for linear-move laterals equipped with pressure reducing valves, *prvs*. The companion manuscripts describe model development and evaluation. The focus of the current manuscript, on the other hand, is on the description of system components, statement of model assumptions, and specification of the lateral hydraulic simulation problem and as such it is intended to set the background for the discussions that follow in the companion manuscripts.

The configuration of the linear-move sprinkler irrigation systems, considered in the current study, and important system components are concisely described here. Furthermore, system attributes that are of particular significance in hydraulic modeling are discussed. Considering that *prvs* are critical to achieving a controlled application of irrigation in linear-move systems, the full range of the operating modes of *prvs* are defined, in the context of irrigation laterals, and their effects on system hydraulics are discussed. In addition, the assumptions that form the basis of the lateral hydraulic simulation model, presented in a companion paper, are stated. Finally, specification of the lateral hydraulic simulation problem is presented and the linear-move lateral is schematized as a branched pipe network, consisting of links and nodes, for hydraulic analysis and simulation.

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