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Furrow Irrigation Modelling: Present and Future

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ABSTRACT: Furrow irrigation is the most common irrigation method practiced in the world because it requires less capital investment compared to pressurized irrigation systems. Despite its wide use, the method is characterized by low performance or low efficiencies. These shortcomings are not inherent to the method but are attributed to poor design, implementation and management. Mathematical simulation of irrigation can lead to improvement in the performance of furrow irrigation systems, without resorting to extensive field experimentation and the commitments of time and money. Researchers developed several mathematical models for simulating furrow irrigation using mass and momentum conservation of physics. However, the existing furrow irrigation models differ in solution techniques, number of sub-modules and applicability. A few models simulate the irrigation impact on the environment, which is the prime concern for sustainable development. Hence, it is necessary to review the existing furrow irrigation models and to modify the modelling approach for attaining efficient water application and for mitigating environmental pollution. This paper presents review on status of furrow irrigation modeling and some of the issues that need to be addressed to make furrow irrigation models suitable for sustainable management of furrow irrigation.

INTRODUCTION

Irrigation has acquired increasing importance in agriculture sector worldwide. It has helped to boost agricultural yields and outputs and stabilizes food production and prices. The statistics reveal that from just 8 m ha in 1800, irrigated area across the world increased (five folds) to 40 m ha in 1900, to 100 m ha in 1950 and to just over 255 m ha in 1995, to 277 m ha at present (Framji *et al.,* 1981; Field, 1990; The World Fact Book, 2003). Further, the world's per capita irrigated land is decreased from 0.044 to 0.042 ha during 1995 to 2006, respectively, which shows the impact of population rise and conversion of agricultural lands to housing and industrial purposes. The irrigation sector, using almost 70% of available fresh water, has remained the single largest user of water. Because, it takes an enormous amount of water to produce crops: one cubic meter to yield one kilo of grains and one to three cubic meters to yield just one kilo of rice. Current global water withdrawals for irrigation are estimated at about 2,000 cubic kilo meter per year. However, with increasing municipal and industrial needs, the irrigation share of water use is likely to go down in future. Moreover, FAO has estimated that overall water use efficiency in irrigation ranges around 38% in developing countries and has projected only a minor increase in overall water use efficiency in the forthcoming decades. Thus, in future, irrigation has to become efficient and produce more with less water. Hence, necessary management measures have to be taken urgently to use irrigation water efficiently for sustainable development.

The practice of application of water (irrigation) to the plant is thousands of years old and as much as 90% of irrigation in the world is by surface methods (Tiercelin and Vidal, 2006). Among surface irrigation methods, the furrow irrigation is very common. It is favoured over pressurized irrigation methods due to lower capital and operating costs, the simplicity of maintenance and the utility of unskilled labour. Typical water application efficiencies for unimproved furrow irrigation systems range from 45 to 60%. Using careful management, improved water control and re-use of tail water runoff, growers can boost efficiencies to 70 to 85%.

Furthermore, furrow irrigation has also raised several environmental concerns owing to loss of fertile soil layer due to irrigation-induced erosion and

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transport of soil-adsorbed agricultural chemicals leading to serious water quality degradation. Thus, to attain a sustainable agricultural development, it is important to improve the existing irrigation system and management practices and to have a better understanding of the irrigation hydraulics, sediment and sediment-adsorbed chemical transport phenomena during irrigation.

Mathematical simulation of furrow irrigation hydraulics can lead to improve the performance of irrigation system, without restoring to extensive field experimentation and the associated commitments of time and money. The main aim of this article is to present a brief description of the past and present research in development of mathematical models for simulating furrow irrigation. Efforts are also made to identify the challenges in the modelling approach and the future directions to improve the existing modelling approach to develop environmental friendly models for sustainable development.

MODELLING FURROW IRRIGATION

In furrow irrigation, the flow process is described in four phases, namely, advance, storage, depletion and recession. Irrigation models generally developed to simulate all these four phases as illustrated in Figure 1.

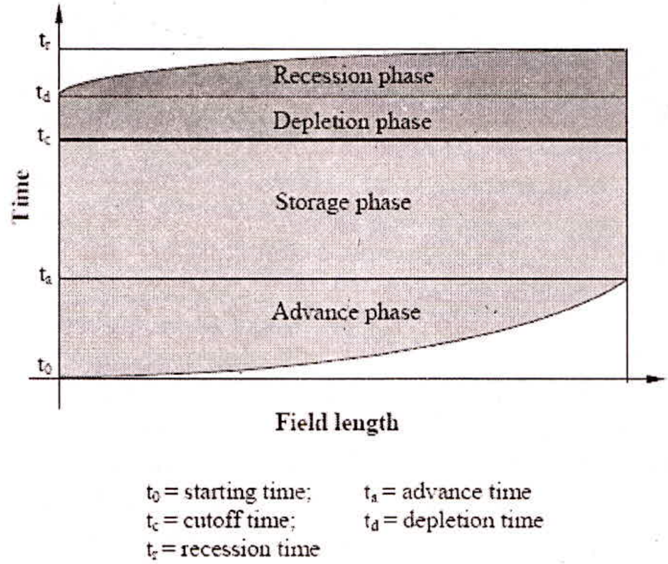

Fig. 1: Phases of furrow irrigation

When water is applied to the field at one end, it advances down to the end of the field. Thus, from the time water is introduced ($t = t_0$), until it spreads and reaches the down stream end of the field ($t = t_a$) is called the *advance phase*. As the inflow continues, the applied water alters the surface and sub-surface water and is described as the *storage phase*. Storage ends at the time $t = t_c$, when the inflow to furrow is cut off. Once, the inflow is cut off, the ponding depth slowly decrease and comes to zero at the head end at time $t = t_d$. This is called *depletion phase*. After some time ($t = t_r$), the ponding depth at downstream end also drops to zero, making that the water is disappeared completely from the surface, which is known as *recession phase*. The shape of these curves, in turn, determines the uniformity, adequacy and efficiency of irrigation. For the optimum design and management of irrigation system, these curves should be parallel, giving uniform infiltration opportunity time throughout the length of furrow. Simulation of these curves is the primary objective of the furrow irrigation models.

Flow Modelling

In furrow irrigation, infiltration causes the variations in the flow depth spatially and temporally. Furthermore, the depth of flow along the field length varies gradually. The flow in furrow irrigation, therefore, is an example of unsteady, non-uniform and gradually varied flow over a porous bed. The hydraulics of unsteady state gradually varied overland flow is described by the Saint-Venant equations, after A.J.C. Barre de Saint-Venant (Chow, 1959) which are the well-known partial differential equations of two physical principles: conservation of mass and momentum (Newton's second law of motion).

The conservation of mass equation is given by,

$$\frac{\partial A}{\partial t}+A\frac{\partial u}{\partial x}+u\frac{\partial A}{\partial x}=-q \qquad \ldots (1)$$

The equation of momentum is given by,

$$\frac{1}{g}\frac{\partial u}{\partial t}+\frac{u}{g}\frac{\partial u}{\partial x}-\frac{qu}{gA}=\left(S_0-S_f\right)-\frac{\partial h}{\partial x} \qquad \ldots (2)$$

where, A is the flow cross-sectional area (m^2), q is the infiltration rate per unit length of furrow (m^3 s^{-1} m^{-1}), x is the horizontal distance (m), t is the time (s), u is the flow velocity (m s^{-1}), g is the acceleration due to gravity (m s^{-2}), h is the flow depth (m), S_0 is the field slope (m m^{-1}) and S_f is the friction slope (m m^{-1}).

The momentum equation is often simplified or in some cases ignored completely to reduce the computational difficulties. The models based on these equations can be grouped in decreasing order of complexity into four sub-classes: (i) Full Hydrodynamic Models (FHM), (ii) Zero-Inertia Models (ZIM), (iii) Kinematic Wave Models (KWM) and (iv) Volume Balance Models (VBM). The governing flow equations are generally solved numerically at a succession of time or space instants, where the solution at the end of the time/space step is stemming from that at the begin. In most cases, the equations are too complex to solve analytically, although analytical and semi-analytical solutions have been developed for the more approximate models (e.g., ZIM, KWM and VBM). With all correct numerical solution techniques, the results will converge toward a limit as step sizes in time and space are reduced. Walker and Skogerboe (1987) presented the derivation and discussion of these surface irrigation models along with their solution techniques.

Full Hydrodynamic Model (FHM)

FHM is based on both the equations of conservation of mass (Eqn. 1) and momentum (Eqn. 2). It is the most accurate and realistic model for simulating surface flow. The accuracy of these models under a wide range of slopes, roughness, inflow rate and infiltration characteristics makes it possible to consider them as standard models for evaluation and calibration of simpler irrigation models. The governing equations, in general, are solved using numerical techniques. The solution techniques used for this model are most complex and require extensive programming and considerable computational time (Bassett *et al.,* 1980; Esfandiari and Maheshwari, 2001). The models have limitations with respect to the availability of data, numerical instabilities (due to highly non-uniform flow) and convergence. In order to gain the numerical stability, special forms of the method of characteristics are used (Schmitz *et al.,* 1985), where the two partial differential equations are transformed into four ordinary differential equations. The other methods used for solving these hydrodynamic equations are method of characteristics (Kincaid, 1970), deformable control volume (Strelkoff and Katapodes, 1977), finite element method (Souza, 1981), Shooting method (Wallender and Rayej, 1990; Bautista and Wallender, 1992) and Preissmann double sweep technique (Mcclymont *et al.,* 1999). These techniques involve time (Mcclymont *et al.,* 1999) and space (Kincaid, 1970; Bautista and Wallender, 1992; Mcclymont *et al.,* 1999) solutions. Space solutions are better adopted to situations in which changes in system properties, such as infiltration parameters, furrow geometry and roughness, need to be stipulated in space.

Zero-inertia Model (ZIM)

ZIM is the simplified form of FHM without the acceleration and inertia terms. According to Katopodes and Strelkoff (1977), the forces acting on the surface stream are basically in equilibrium for the Froude number less than 0.3. In other words, at low velocities normally encountered in irrigation discharges, the change in velocities with respect to time and space are substantially small, compared to the force terms in the momentum equation (Guardo *et al.,* 2000). Therefore, neglecting the inertia terms in the momentum equation is a valid assumption for furrow irrigation. The momentum equation for the zero-inertia models can be defined by the following equation,

$$\frac{\partial h}{\partial x} = S_0 - S_f \qquad \ldots (3)$$

Equations. (1) and (3) are referred as governing equations for ZIM. The numerical solution of these equations has been presented by Strelkoff and Katapodes (1977). The computational grid is generated during the simulation of the advance phase by the location of the advancing surface stream tip at given constant time steps. Water level and discharge at the calculation-grid nodes are calculated by linearization of the governing equations, which are solved by implicit differences and the double sweep algorithm. These models perform best in comparison with full hydrodynamic models, less expensive to operate and show better numerical performance.

Several investigators (Clemmens, 1979; Elliott and Walker, 1982; Schwankl and Wallender, 1988) applied for furrow irrigation using numerical techniques. Later, Schmitz (1989) developed an analytical solution for the zero-inertia governing equations and developed a model ZIFA for furrow irrigation advance (Schmitz and Seus, 1992). The analytical solution techniques were used by the several researchers for simulating furrow irrigation (Arasteh, 1995; Wohling *et al.,* 2004a, 2004b; Wohling, 2005; Mailapalli, 2006). The solution techniques involve both time (Strelkoff *et al.,* 1998; Schmitz and Seus, 1992; Wohling, 2005; Mailapalli, 2006) and space (Schwankl and Wallender, 1988; Wohling, 2005) solutions.

Kinematic Wave Model (KWM)

In KWM, in addition to the above zero-inertia assumption, the water-depth gradient (i.e., $\partial h/\partial x = 0$) is neglected. Therefore, Eqn. (3) can be further simplified by neglecting the depth gradient and inertial terms to yield the following equation,

$$S_0 - S_f = 0 \qquad \ldots (4)$$

It means that the depth of flow at a point along the furrow is uniform. In other words, the bottom slope is equal to the friction slope, which however, may some times yield misleading results. KWM was initially developed for hydrologic applications (Lighthill and Whitham, 1955) and then applied to sloping free drained borders (Smith, 1972). The kinematic-wave approach has been used by a number of investigators to develop models of furrow irrigation (Walker and Humpherys, 1983; Rayej and Wallender, 1988; Bautista and Wallender, 1992; Fonteh and Podmore, 1994; Raghuwanshi and Wallender, 1997). Investigators often justify the kinematic-wave assumptions by its low mathematical and computational costs and its comparatively high accuracy, which is proven by field experiments. Though the KWM has been used for various phases of irrigation, it violates the momentum equation for small slopes, short furrow lengths and large inflow rates (Spurgeon and Duke, 1988). The solution techniques include both time (Rayej and Wallender, 1988) and space (Wallender and Yokokura, 1989; Reddy and Singh, 1994; Raghuwanshi and Wallender, 1996) solutions.

Volume Balance Model (VBM)

In VBM, the momentum equation was neglected completely to make the solution further simple and assume some shape factors for surface and infiltration profiles. Lewis and Milne (1938) were probably the first to develop a volume balance approach to predict waterfront advance in border irrigation. Davis (1961) was probably the first to use the concept of volume balance in furrow irrigation. The irrigation advance function can be approximated by a power function, which lead to much simpler analytic volume balance expression (Fok and Bishop, 1965; Elliott and Walker, 1982; Walker and Skoerboe, 1987). Valiantzas (2000) developed explicit advance-time equations with variable surface and sub-surface shape factors. The other investigators used the volume balance approach for simulating furrow irrigation are Wallender (1986), Yu and Singh (1990), Eldeiry *et al.* (2004), etc. Nevertheless it provides satisfactory results for many problems; its application is limited to narrow range of conditions (Strelkoff and Katopodes, 1977). Moreover, assumption of surface flow profile in this approach introduces empirical aspects. Upadhyaya and Raghuwanshi (1999) used volume balance technique for developing semi-analytical model for furrow infiltration. Renault and Wallender (1992) developed ALIVE (Advance Linear Velocity) model based on flowrate water balance by considering a constant inflow rate, a homogeneous infiltration function along the run and a constant mean section.

Generally, VBM is not appropriate for field management and design purposes since their empirical parameters do not account for conditions of the irrigation system, which are different from that of calibration. Moreover the comparative low accuracy of VBM is caused by the gross assumptions of the flow equations, e.g. the time and space-invariant flow depth (which is not influencing infiltration), the unrealistic description of flow over a dry surface and the merely empirical infiltration functions.

Modelling Infiltration

Most surface irrigation models use empirical equations to calculate the volume of infiltrated water. Probably, the Kostiakov (1932) equation modified by Lewis (1937) is the most predominantly used empirical equation in surface irrigation models (Schwankl and Wallender, 1988; Wallender and Rayej 1990; Yu and Singh, 1990; Bautista and Wallender, 1992; Raghuwanshi and Wallender, 1997; Valianzas, 2000; Eldeiry *et al.,* 2004) due to its simplicity of relating cumulative infiltration to the infiltration opportunity time. Since an empirical equation is fitted to the observed infiltration data, it only represents the observed event and may not represent different fields or different irrigation events.

To overcome the limitations of empirical based infiltration equations, physically based infiltration equations were developed based on the Green and Ampt (Green and Ampt, 1911) and Richards' (Richards, 1931) equations. Fok and Chiang (1984) conceptualized a 2D-infiltration model, based on the Green and Ampt model, consisting of three separate infiltration zones (vertical, horizontal and sides) which all contribute to total infiltration. Singh *et al.* (1987) also recognized the need to consider 2D-infiltration for designing furrow irrigation systems. They developed a generalized infiltration model based on the stream tube concept using the continuity equation, energy equation and Darcy's law and extended the model to 1D, 2D and 3D cases. Fonteh and Podmore (1993) developed a quasi two-dimensional infiltration model composed of 1D-vertical Green Ampt model, 1D-horizontal infiltration (Hansen, 1955) and a transition zone between the two rectangular flow domains. Schmitz (1993) treated the 2D-infiltration process as a sum of weighted 1D-infiltration processes in separate soil columns, particularly noting the influence of the shape of the furrow profile on infiltration. Infiltration is calculated using an analytical solution of 1D-modified Richards' equation. Tabuada *et al.* (1995) has coupled the hydrodynamic flow equations with two-dimensional

Richard's equation for furrow irrigation. Enciso-Medina *et al.* (1998) developed a two-dimensional (2D) infiltration model using Green and Ampt approach that incorporates the effects of surface sealing, soil cracking and initial soil water content. The model was compared with a finite difference solution of the Richards equation for vertical infiltration for two surface seal conditions. Skonard and Martin (2002) developed a physically based 2D-infiltration model for furrow irrigation using Green and Ampt infiltration method and the performance of the model was tested with a finite element model, HYDRUS-2D. Wohling *et al.* (2004a) developed a semi-analytical furrow infiltration model (FURINF), which portrays 2D-infiltration from the wetted furrow perimeter by a series of 1D-infiltration computations that are performed on the basis of an analytical as well as a numerical solution of the 1D-Richards' equation. Recently Mailapalli (2006) used Green and Ampt approach for developing 1D (Rao *et al.,* 2006) and 2D-infiltration (Fok and Chiang, 1984) models and coupled with zero-inertia overland flow model for simulating furrow irrigation.

Wallender and Rayej (1987) studied the effects of spatial variability in infiltration on the maximum economic return of water for furrow irrigation. Using a seasonal furrow irrigation model, furrow irrigation schedules and designs were optimized for homogeneous and heterogeneous infiltration conditions, considering heterogeneity in soil moisture depletion and irrigation nonuniformity for fixed and variable interval irrigation scheduling criteria (Raghuwanshi and Wallender 1997a, 1998). Earlier studies (Bautista and Wallender, 1985; Wallender, 1986; Bali and Wallender, 1987; Rayej and Wallender, 1988 and Schwankl and Wallender, 1988) compared infiltration measurements along furrows with simulated infiltration assuming constant and varying soil infiltration characteristics. Oyonarte *et al.* (2002) applied the combination of variance technique to analysis of the contribution of sources of variability to the uniformity of the infiltrated depth. Yonatan and Mateos (2003) developed a method for evaluating furrow irrigation accounting for spatial variation in infiltration using the kinematic-wave approach.

Sediment Transport Modelling

Israelson *et al.* (1946) first used an empirical model as suggested by Willard Gardner in 1938 for predicting soil erosion from furrow irrigation experiments on silty-clay-loam, loamy-sand and sandy-loam soils. The model suggested that the erosion on a given furrow slope is dependant on the stream size and length of the furrow. Fornstrom and Borrelli (1984) developed a regression model using extensive field data of soil loss from irrigation furrows in various field conditions, soil texture, flow rate, length of run and slopes.

Physically based models are based on the solution of fundamental physical equations describing stream flow and sediment transport in irrigation furrows. Standard equations used in such models are the equations of conservation of mass and momentum for flow and the equation of conservation of mass for sediment (Bennett, 1974). Wu and Meyer (1989) developed a conceptual, physically based model, ROWERO for simulating transport of non-uniform sediment along flatland furrows. The surface runoff and sediment transport are routed with kinematic wave and sediment continuity equations and found that ROWERO over predicted sediment discharge rates for most cases. Strelkoff *et al.* (1998) developed a computer program, SRFR for simulating surface irrigation. It provides estimates of soil erosion, flux and deposition at various points along the furrow as functions of time. The sediment transport formulae were chosen as Laursen (1958), Yang (1973) and Yalin (1963).

WEPP (Water Erosion Prediction Project) is a physically based model, which was used by many authors (Bjorneberg *et al.,* 1999; Trout, 1996) for predicting flow and sediment transport in furrow irrigation. The WEPP-furrow irrigation component comprises overland flow, infiltration and sediment transport as sub-components that are modelled with kinematic wave model, 2D-approximation of Green and Ampt infiltration equation as presented by Fok and Chiang (1984) and steady state sediment continuity equation, respectively. Since its release in 1995, users have noted problems in applying WEPP to irrigated furrows, citing major discrepancies between simulation and field-measurement of both infiltration/deposition profiles (Bjorneberg *et al.,* 1999; Bjorneberg and Trout, 2001). A review of the supporting documentation and literature revealed a number of unnecessary and possibly flawed assumptions within the hydraulic components of the model. Recently, Mailapalli (2006) developed a physically based model (ZIGASED) for simulating flow and sediment transport in furrow irrigation. ZIGASED uses a steady state sediment transport model in which the sediment transport capacity was determined with Yalin (Yalin, 1963) and modified Yalin equations (Finkner *et al.,* 1989).

Seasonal Furrow Irrigation Models

The seasonal furrow irrigation models should include the irrigation scheduling component to advise the farmers 'when to irrigate' and 'how much to irrigate'. Irrigation scheduling is necessary to satisfactorily maintain a good soil moisture status in the root zone reservoir and thereby provide near optimum environmental conditions for crop growth. For furrow irrigation systems, the control is not the method of applying water but rather the soil surface. More specifically, the infiltration function is the major concern in replenishing the root zone reservoir. The combination of infiltration function and time of advance function dictates the hydraulic performance for an irrigation event. Unfortunately, both of these functions change dramatically from one irrigation event to the next during a season, as well as showing year-to-year variations.

Researchers also developed seasonal furrow irrigation models using one of the four irrigation modelling approaches. Raghuwanshi and Wallender (1996) developed a seasonal furrow irrigation model, which include irrigation schedule (water balance), irrigation design (irrigation hydraulics) and crop yield (yield function) under spatially and temporally variable conditions. They optimized furrow irrigation schedules and designs for homogeneous and heterogeneous infiltration conditions considering heterogeneity in soil moisture depletion and irrigation non-uniformity for a fixed interval irrigation scheduling criterion (Raghuwanshi and Wallender, 1997a) and for a variable interval irrigation scheduling criterion (Raghuwanshi and Wallender, 1998). Later the authors (Raghuwanshi and Wallender, 1997b) modified the seasonal irrigation model with economic optimization module and simulated for irrigation of complete cropping season. Ito *et al.* (1999) have used partial information from furrow geometry and infiltration within a KW model combined with an economical optimization model to design furrows. Recently, Motesinos *et al.* (2001) developed OPTIMEC (EConomics OPTImization in Spanish) for determining quasi-optimum irrigation season calendar based on economic profit maximization.

FURROW IRRIGATION MODELS

The potential for improving the efficiency and performance of furrow irrigation systems lies in the use of simulation models to predict furrow irrigation performance and assess changes in management variables, which can lead to improvements in irrigation efficiency. A number of such models have been developed using the above mentioned modelling approaches. A few of these models have also been developed into user friendly computer programs with the ultimate aim of being used by irrigation practitioners as Decision Support Systems (DSS). These include the SRFR (USDA, 1997), SIRMOD (Walker, 1998), FIDO (McClymont *et al.,* 1998), SURDEV (Jurriens *et al.,* 2000). These models use numerical techniques to solve the hydrodynamic equations. Also, considering the numerical difficulties in the solution procedure, Schmitz and Seus (1992) developed an analytical model, ZIFA to predict advance in furrow irrigation. All these models, generally, use the Kostiakov infiltration equation to model sub-surface flow only through uniform soils. Moreover, these models seldom include irrigation-induced erosion. Only recently, the United States Water Conservation Laboratory has modified the existing surface irrigation model, SRFR, to simulate water and sediment transport processes together. However, the erosion module of SRFR is also based on empirical relationship (Strelkoff and Bjorneberg, 1999).

Technological developments are now rapidly occurring regarding the control of on-farm discharges using Best Management Practices (BMPs) such as conservation tillage and cover cropping. Therefore the irrigation hydraulics has to be modified based on the soil management in furrow irrigation. The runoff from furrow irrigation contains variety of pollutants which needs to be studied and modeled. However, there is the important question regarding the state-of-the-art knowledge in ecological modelling applied to irrigated agriculture and the subsequent question of high priority research needs. But, technology can only be a partial solution. Consequently, more important is the question of processes that can be employed to alleviate environmental degradation resulting from irrigated agriculture.

CHALLENGES AND FUTURE DIRECTIONS

Flow Modelling

Most existing models simulate the flow for a single furrow under free drained and uniform soil conditions. Therefore the modelling approach needs be extended to whole field for different furrow types (free drained, closed end, alternate furrow, etc.) by considering the variability in the soil's physical and hydraulic properties. In reality, farmer does not know how much inflow is given to each furrow other than the inflow to the whole field. Hence, using the inflow information, the model should estimate the inflow at each furrow based on the application device (gates or siphons) used. The soil moisture status at regular intervals will be useful for irrigation scheduling and the outflow from each field indicates the on-farm irrigation contribution to the streams. Furthermore, the irrigation models should account the effect of soil management practices such as conservation tillage and cover cropping, effect of seasonal soil changes such as compaction, cracks, rodent holes, seal formation, etc. and the effect of biological agents such as earthworms, etc. Various furrow geometries must also be considered in 2D-infiltration model as curvature and wetted perimeter strongly affect the infiltration.

Sediment Transport

Due to the several complex processes discussed previously, soil erosion, transport and deposition in furrows is much more difficult to quantify than is represented by these simple models. Relationships that were originally developed to model erosion and transport in large non-cohesive channels cannot accurately predict erosion in small cohesive furrows, although they do provide valuable information on factors and relationships important to the process. Our lack of understanding of soil cohesion and aggregate stability further limits the effective use of analytical models. Thus, although process-based models are important for understanding the processes, the presently available models can predict soil erosion from a field no better than simple empirical models relating erosion and sediment transport to measurable hydraulic parameters such as slope and flow rate and quantitative description of the soil medium. Therefore, the models should include the morphological changes of furrow due to flow and erosion dynamics. Also, the models need to incorporate the lateral flow component into the furrow during the rainfall. This suggests that furrow irrigation modellers need to reformulate the mass and momentum equations so that the future furrow irrigation models simulate the flow and sediment transport during both irrigation and rainfall events.

Nutrient and Pesticide Transport

Recently, Crevoisier *et al.* (2008) simulated nitrogen transfer from different furrow irrigation systems (every furrow and alternative furrow) using HYDRUS-2D (Simunek *et al.,* 1999). However, none of the furrow irrigation models incorporate the nutrient and pesticide transport. The two nutrients most commonly investigated in irrigation system are nitrogen and phosphorus. Phosphorus is tightly held by soil particles and essentially all phosphorus encountered in surface runoff from irrigated lands is associated with sediment. Generally, soluble forms of nitrogen and phosphorus are transported in the runoff and insoluble forms and forms adsorbed to sediment particles are moved by erosion. Nitrite is the principal nutrient form leached to ground water or base flow by percolating water. The plant nutrient sub-model should have a nitrogen component that considers mineralization, nitrification and denitrification processes. It should estimate the plant uptake and nitrate leached by percolation out of the root zone. It also should estimate the amount of nitrogen and phosphorous transported by the sediments (i.e., the amount of nutrient adhere to the sediments).

The pesticide component should consider foliar interception, degradation and washoff, as well as adsorption, desorption and degradation in the soil. This method, like the nutrient model, may use enrichment ratios and partitioning coefficients to calculate the separate sediment and water phases of pesticide loss. The schematic view of the proposed furrow irrigation model for nutrient component may be conceptualized as in Figure 2.

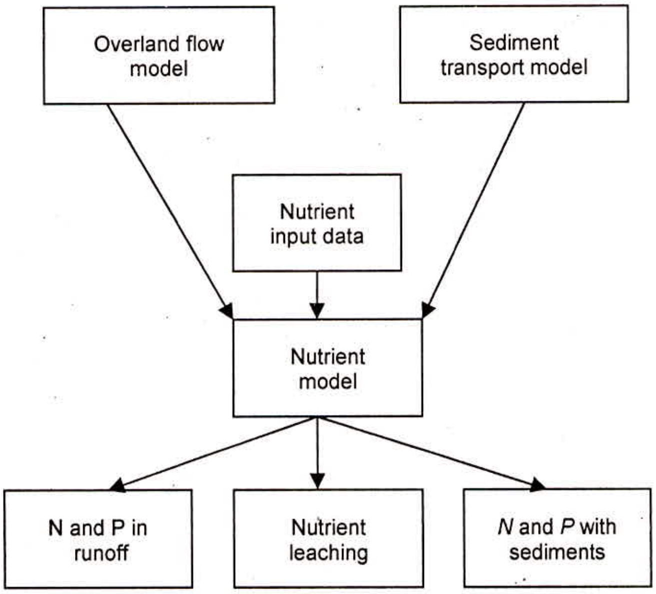

Fig. 2: Schematic view of the furrow irrigation model for nutrient transport

The use of chemicals is an important feature of modern agriculture, but the movement of the chemical from its point of application constitutes a potential hazard. Mathematical models play an important role in evaluating this hazard. The models may have to describe the movement of chemicals from the agricultural fields. In each irrigation, the objective is to use the model to predict the concentration of a chemical in the runoff water, the total amount carried by the runoff water and sediment and the location and concentration of the chemical remaining on the field.

Chemicals adsorbed to the soil are subjected to erosion as a transport mechanism. The chemical concentration in the soil varies with the depth because of the application method and the amount of leaching. Therefore, surface erosion is calculated. Finally, a decrease in the transport capacity of the runoff can cause deposition of the sediment. Chemicals are usually preferentially adsorbed by the finer sediment fractions, which are the last to be deposited and, therefore, the composition of the sediment, which is enriched with the fine material, is calculated. In summary, the erosion sub-model supplies the chemical sub-model with estimates of furrow erosion, area and depth of furrow, amount of deposition and the enrichment of the eroded sediment relative to the clay fractions of the original soil. The outline of the modelling chemical movement over the irrigated fields may be similar to the case of nutrient transport described above (Figure 2).

Plant Growth Simulation

Recently, researchers achieved important developments in simulating plant growth. An understanding of crop physiology is required for such simulations. The model structure relies on defining the relation between individual foliage elements and their environment, then integrating over the canopy to determine the collective effect. The irrigation models should include a general, comprehensive, detailed plant model describing both root and canopy growth taking into account photosynthesis, respiration, transpiration and soil hydraulics. This model can be used to trace root growth and distribution under different soil and climatic conditions and to assess potential effects of alternative irrigation strategies on crop response, as well as upon such processes as evaporation and drainage. These models predict on a daily basis the crop's response to its environment. Such predictive tools are highly important in evaluating management alternatives during the season upon crop yields and eventually net income.

SUMMARY

In the past, several innovations have been taken place in furrow irrigation modeling which include different solution techniques and assumptions for solving flow equations leading to different models, considerations of spatial and temporal variability, physically based infiltration, sediment modeling, integration of optimization and scheduling components with hydraulic models etc. However, currently available models are not comprehensive, if they consider one aspect then lack on other aspects. To develop sustainable irrigation management plan at field scale, a very comprehensive furrow irrigation model that can simulate flow, sediment, nutrient and pesticide transport and nutrient and water uptake by plants considering spatial and temporal variability of soil and crop condition need to be developed. Such model can be used to decide flow rate and cutoff time for individual furrows, irrigation timing, fertilizer and pesticide application rate, etc. in an optimal manner which would help in meeting sustainable development goals.

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