Hydraulic classification of irrigation supply systems

Classification hydraulique des systèmes d'alimentation d'irrigation

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ABSTRACT

Modern irrigation supply systems have diversified and yet methods of their classification have been overlooked. Thus, each system appears unique and this makes it difficult to integrate experience gained from their analysis. This paper postulates that "hydraulic command" is responsible for their diversification and creates "generic" variations among irrigation systems with each command method making up one class; conversely the systems associated with the same class or hydraulic command share the same generic complexities. The benefits of classification are methodological and include (**i**) gaining an insight into technical/ management issues associated with each class; (**ii**) obtaining an overview of generic variations across the classes of these systems enabling integration of knowledge; (**iii**) explaining mutual incompatibility of the systems associated with different command methods.

RÉSUMÉ

Les systèmes modernes d'alimentation d'irrigation se sont diversifiés, cependant leur classification a été négligée. Chaque système apparaît donc comme unique ce qui rend difficile de tirer parti de l'expérience acquise à partir de son analyse. Cet article postule que la "commande hydraulique" caractérise leur diversification et crée des variations "génériques" parmi les systèmes d'irrigation, chaque méthode de commande constituant une classe; réciproquement, les systèmes associés avec la même classe ou commande hydraulique, partagent les mêmes complexités génériques. Les bénéfices de la classification sont méthodologiques et permettent: **(i)** d'avoir une idée des problèmes techniques et de gestion associés à chaque classe; **(ii)** d'obtenir une vue d'ensemble des variations génériques entre les différentes classes de ces systèmes pour permettre une intégration de la connaissance; **(iii)** d'expliquer l'incompatibilité de systèmes associés à des méthodes de commande différentes.

Key words: irrigation, diversification, problemsolving, insight, generic variations, command, connectivity

1. Introduction

Irrigation systems have diversified with the underlying technical and management issues aggregated and interrelated. Each of these systems may seem unique and with their large numbers worldwide, they are hardly expected to display any pattern. Discussing an apparent inability to classify "generic variations" amongst these systems, Chambers (1988) states that "in default of a diagnostic typology, each system has to be treated as unique." He asserts that "if there are types of canal irrigation systems, the principles of classification are not well developed." To the knowledge of the author, the need for such a classification is overdue and argues that, the growing body of international experience on problemsolving of these systems can remain project-specific but this is counterproductive. This paper shows that "hydraulic command" can be used to classify these systems. The contribution of this paper is methodological, in that without introducing a new method, existing knowledge on the subject is reorganised.

Irrigation systems are engineered to convey water from where it is available and often not needed to where it is not available but needed. The conveyance is achieved under hydraulic command, defined as the ability to make water flow in these systems whilst flow conditions are designed to remain within prescribed permissible ranges. A full range of hydraulic command methods is presented in this paper, which are depicted in Fig. 1 and detailed later in the paper, with each method representing a class of irrigation systems and marking up a different level of complexity. The method of characteristics plays a key role in the conceptualisation of each command method. This paper postulates that each command method makes up one class of irrigation systems and each class is characterised by a clearly defined level of complexity at physical, technical and social dimensions. The postulate is substantiated by presenting evidence from international implementation of these systems.

Each command method is associated with two fold differences. (**i**) There are "minute" but generic variations from one command method to another, related to the propagation of "hydraulic signals" along "characteristic directions." (**ii**) There is a large number of irrigation systems associated with each class of command methods; conversely the systems associated with the same command method display similar generic identities but differ from one another in different arrangements of their constituent "components" and hydraulic "processes." These are detailed later but some of their salient points are outlined in Fig. 1.

Irrigation systems are compositions of components, such as canals, regulators, and offtakes, which are normally associated with such processes as boundary, local, spatially-distributed and control processes, see Fig. 1. Hydraulic command of an individual system is neither a component nor a process but systems associated with the same command method display similar generic complexities. Conversely, a particular command method is often associated with a particular selection of components, processes and management issues, see Fig. 2. Generic variations associated

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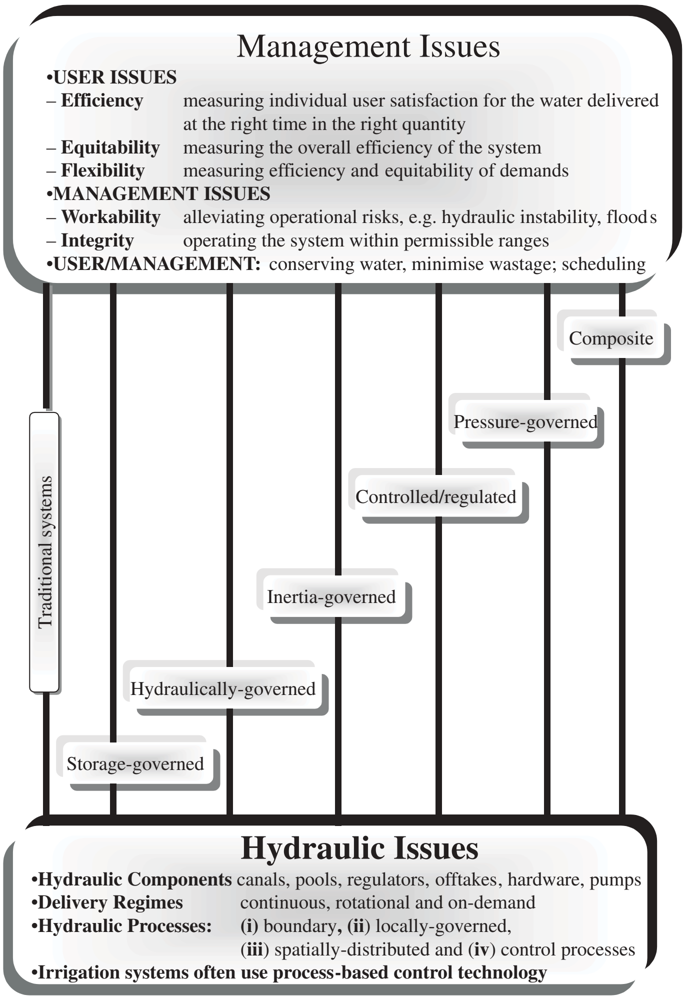


Fig. 1. Hydraulic Command Methods.

with each of the command methods are described throughout the paper to reveal the freedoms and restrictions associated with each class of irrigation systems. Knowledge of the method of characteristics is assumed in this paper. The terms hydraulic command and command methods are used interchangeably but the verb command means to govern flow.

2. Conceptual Context of the Postulated Classification

Gravity governs flows in many traditional irrigation systems, where influencing the distribution of flow conditions by hydraulic structures is not often feasible. Although these systems have often been integrated to local market patterns, their performances are restricted to subsistence economy and lack facilities for accommodating fluctuating demand or supply. Thus, innovative techniques were inevitable and their first signs could be traced to large-scale plantation agricultural schemes implemented by colonial powers in the 17th and 18th centuries, which could be seen as prototype irrigation enterprises. These often comprised the distribution of stored water through large canals without any significant control structures. Since the 19th century these systems have been implemented as enterprises but often at the expense of inducing adverse environmental impacts. Modern systems have been engineered exploiting all the possible methods of hydraulic command and with a recent emphasis on sustainable developments.

Holistic problemsolving methodologies have become widespread since 1980 for being capable of preventing the loss of synergy but such a loss was inevitable in traditional problemsolving approaches based on breaking a system into components. However, Chambers (1988) criticises the manner of application of holistic approaches in recent publications, holding them to be descriptive. He presents the “diagnostic analysis method,” which is a holistic approach but capable of explaining many of the inherent blind spots. Nonetheless, Chambers acknowledges that classification of irrigation systems is an important issue and outstanding. He likens the current problemsolving stage of irrigation systems without classification to the stage of biology prior to Carlos Linnaeus (1707-78) originating a first method of classification in biology. The contribution of this paper is to fill the gap on the lack of a classification method to explain generic variations of information across the whole spectrum of irrigation systems.

2.1 Issues on each of Class of Irrigation Systems

Best condition for scheduled water distributions in irrigation systems is steady deliveries, in which hydraulic properties of water (*e.g.* depth, discharge, velocity) do not change with time. However, changes are likely due to gradual or operational changes. These give rise to sets of issues, outlined in Fig. 1 for all classes and in Fig. 2 for each class irrigation systems.

2.2 Basic definitions

The driving force inherent in hydraulic command is gravity or pumpage. Gravity is effected by the elevation of source-water being higher than its command areas. Pumpage serves as either to pressurise the flow in closed conduit systems or to lift water to compensate for insufficient command. Any of these driving forces are by design through the contribution of the following measures (*a*) channel geometry, (*b*) alignment of conveyance channels (*c*) a host of hydraulic/control units, and (*d*) interactions with social context.

Generic variations associated with each hydraulic command may be determined in terms of (**i**) propagation of **hydraulic disturbances**, (**ii**) provisions of **hydraulic connectivity** by the virtue of in-channel storage or elastic pipe boundaries for the propagation of disturbances (**iii**) **response times** for disturbances to propagate from one point to another. These are associated with one another in the characteristics equations outlined below.

Open-channel and closed conduit unsteady/transient conditions are governed by quasi-linear partial differential hyperbolic equations. Hydraulic disturbances are defined as variations of velocity, v, and depth of flow (pressure head), y, with space, x, and time, t, represented by

$$\frac{\partial v}{\partial t},\ \frac{\partial v}{\partial x},\ \frac{\partial y}{\partial t} \text{ and } \frac{\partial y}{\partial x}.$$

These disturbances are transformed into hydraulic signals expressed by (1) below in mathematical terms through the method

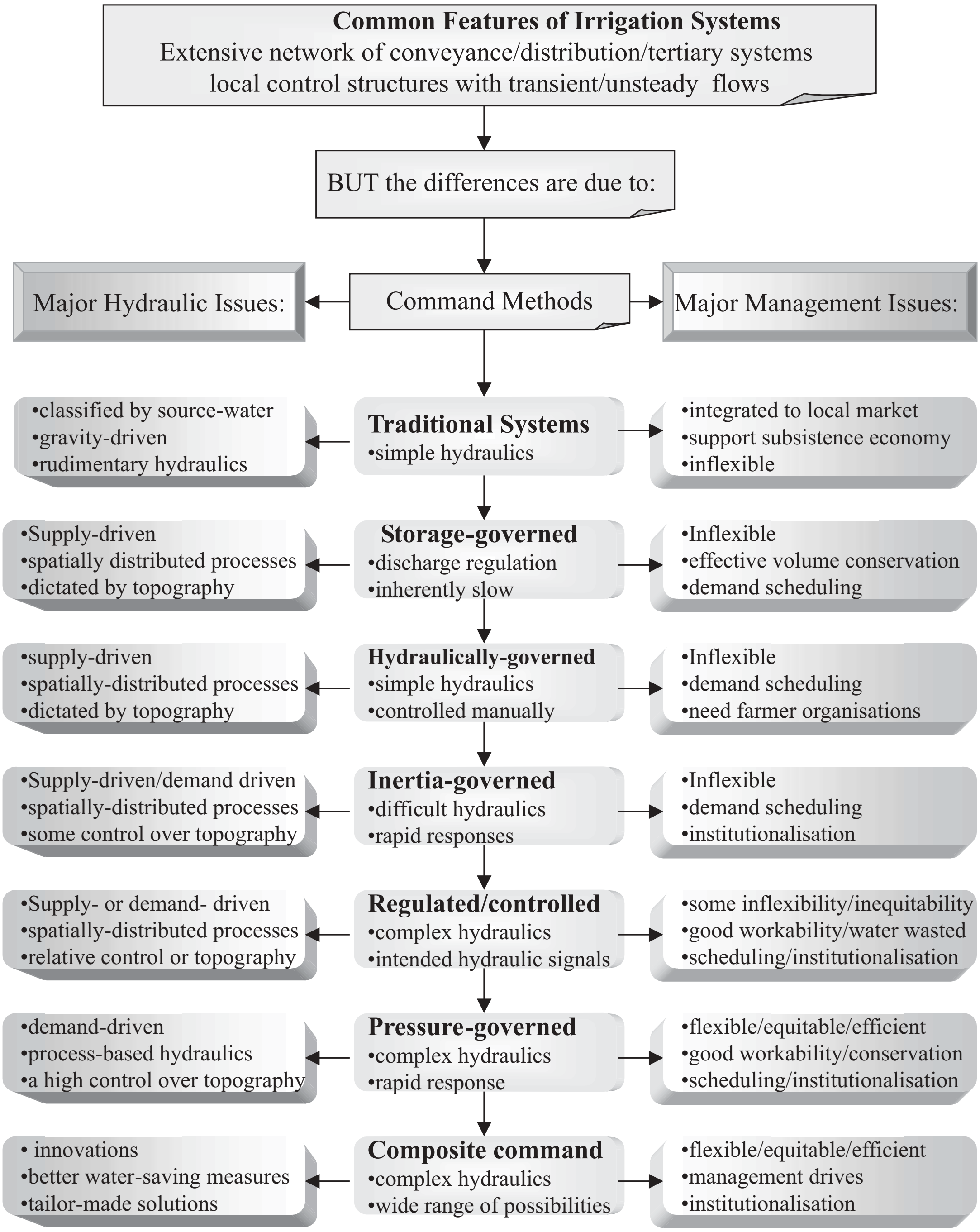


Fig. 2. Major Hydraulic and Management Issues Associated with each Command Method.

of characteristics, resulting in a set of ordinary differential equations (see Jaeger 1964):

$$\frac{dv}{dt} \pm \frac{g}{c}\frac{dy}{dt} = g(S_0 - S_f) \tag{1}$$

where, g= acceleration due to free fall, S_0, S_f = gravity and friction gradients, v= bulk velocity and c= wave celerity. Generic variation of each hydraulic command refers to hydraulic information defined by (1). These hydraulic signals are trains of hydraulic information signals propagated along the **forward** and **backward characteristic directions**:

$$\frac{dx}{dt} = c \pm v \tag{2}$$

Hydraulic connectivity is implicitly defined by (2) based on the presumption that a continuum is required for propagation of hydraulic signals with speed c. The signals created at one part of the system are propagated to another by a provision of ‘‘wedge’’ or ‘‘prism’’ storage in open-channels but in pressurised systems either by elastic pipe boundaries or by mass oscillation in rigid pipes. If storage provisions are not maintained under some operational conditions, disturbances will be dissipated rapidly and the water will move with its bulk velocity. Thus, it is argued that as soon as the storage provision is depleted in any part of a system, there is no more **hydraulic connectivity in the system for the**

propagation of hydraulic signals. In pressurised systems with elastic boundaries, hydraulic connectivity is always maintained, as long as pressure head is contained within a range below its maximum and above its minimum prescribed values.

This paper has a consistent reference to **response time**, τ, which can be defined in terms of time taken for hydraulic disturbances to propagate. It is calculated as:

$$\tau = \int \frac{1}{c \pm v} dx \qquad (3)$$

2.3 Generic Variations Associated with Hydraulic Command Methods

Generic variations and hydraulic command are interrelated and the following feasible command methods are presented mathematically below and outlined in Table 1 but knowledge of their interpretation is assumed:

1. **Storage-governed** command is related to the kinematic characteristic direction defined by the Seddon-Klietz law and for wide channels this is expressed as:

   $$\frac{dx}{dt} = v_k = -\frac{1}{w}\frac{\partial Q}{\partial y} \qquad (4)$$

   where, v_k = kinematic wave speed and w= channel width.

2. **Hydraulically-governed** command describes irrigation systems under natural hydrodynamic conditions. Since, for shallow water-waves in wide channels $c^2 = gy$, using $2c(dc) = g(dy)$, Eq. (1) can be transformed into (see Henderson 1966):

   $$\frac{d(v \pm 2c)}{dt} = g(S_0 - S_f) \qquad (5)$$

   Under this command spatially-distributed hydraulic processes are strong with a poor control over transient effects.

3. **Inertia-governed** command caters for terrain conditions where deltaic low-lying source-water is below command areas. Obviously, under this condition, irrigation by open channels must be impossible but low-lying source-water can command high-lying irrigated areas through engineered canal systems with a cascade of pumps. Disturbances propagate at:

   $$c \approx \pm\sqrt{gy} \qquad (6)$$

   The characteristic direction governed by (6) is a special case of (5) where, c-values can be high in comparison with (2), with a comparatively faster response time.

4. **Controlled/regulated** command improves hydraulically-governed command methods by innovatory provisions of (**i**) in-channel wedge or prism storage superimposed on the moving bulk of water and (**ii**) a series of cross-regulators. These facilities together with a provision of control technology components filter and retain hydraulic signals governed by (1) and allow the propagation at an intended direction (either upstream or downstream). Thus, these command methods are more advanced and complex than natural command methods of storage-governed, hydraulically-governed and inertia-governed command methods.

Table 1. Attributes of Different Command Methods.

Command methods	**Main assumptions**	**Main features**
Storage-governed command	• $\frac{\partial Q}{\partial y}$ must be small • Changes in storage solely drives variations in water levels	• the water in the system acts as in-channel storage • inherently slow response
Hydraulically-governed command	This command is designed through: • optimised canal sections • aligning the canal along gently falling contour lines	Contouring replaces in-channel storage: • with it, transients are rapidly dissipated • with it, hydraulic variables are kept within a min-max permissible range • without it, steady operations hampered
Inertia-governed command	• the bulk of water acts as in-channel storage • v, S_0 and S_f are insignificant • Pumps maintain the command	• fast propagation of hydraulic signals • difficult hydraulics • risks of hunting • costs
Controlled/ regulated command	• relies on in-channel storage – prism and/or wedge storage • Control components are needed to trigger automatic modulations	• waves directions are filtered and propagated along intended direction(s) • a technological solution • costs
Pressurised command	• propagation of pressures waves through elastic boundaries, or • mass oscillation within the systems	• similar to inertia-governed or regulated / control command methods • highly technological solution and costly

5. **Pressurised command** methods are described by (1)-(2), in which either hydraulic disturbances are transformed into pressure waves propagated through elastic pipes expressed as:

$$c = \frac{g\Delta h}{\Delta v} \qquad (7)$$

where, Δh = change in pressure head and Δv = change in velocity, see Fox, 1977. Alternatively waves are propagated as mass oscillations through rigid pipes, in which changes in pressure head are related to bulk velocity, as:

$$\Delta h = \frac{L}{g}\frac{dv}{dt} \qquad (8)$$

where, L= pipe length and $\frac{dv}{dt}$ ordinary differential expressing the time rate of bulk velocity, see Fox, 1977. Waves propagated in open-channels and closed conduits display generic similarities in terms of mathematics and propagation of hydraulic signals but their physical differences are considerable.

3. Engineering Details of Each Class of Irrigation Systems

Hydraulic commands in traditional systems are created generally by gravity for the distribution of water through dendritic watercourses possibly involving rudimentary hydraulic ancillaries. The remnants of some of these systems are still operational in many parts of the world and the paper suffices to just mentioning some of these systems, which include qanats, spate systems, run-of-river systems, shadufs or Archimedean screw systems, the tank irrigation system, and spring/well systems. A classification of modern systems is presented in more detail, outlining a typical

Table 2. Attributes of Different Command Methods.

Command	Strengths	Weakness	General remarks	International Implementations
Storage-governed	• Simple • Ability to conserve water and regulate discharge	• Extensive land take up • Inflexible • Inefficient	• an onus on the effectiveness of on-farm water-saving measures	Akin to this command are: • many systems in nearly-flat plains of Australia • the Abary River scheme in Guyana - a low-lying flat area with a wide main canal rotationally distributing water to secondary canals
Hydraulically-governed	• simple • self-regulating • fixed equitability pattern	• inefficient • unable to meet variable demand • often with no measuring structures	• widely used in the developing countries • farmer organisations needed	• relics of the 19th Century **normal flow systems** • **systems with proportional deliveries**: - farmer-managed systems in Bali, - proportional weirs in the hills of Nepal and - Warabandi in Pakistan and India since 19th century • **systems with flexible deliveries:** - indent scheduling the Gezira, The Sudan and - the relative area method in Java, see Burton 1989; - the Shejpali scheduling, India, see Rangeley 1989
Inertia-governed	• not particularly flexible • inefficient in conservation	• risks of hunting • difficult operations • skill required	• need modelling studies • provisions of escape structures required • requires demand scheduling & farmer organisation	• water is pumped from the Nile, Egypt, through a cascade of pumped canal pools - a modern replacement for shadufs and Archimedean screws • drained water with lost command lifted back to the top end to blend source-water – e.g. a number of schemes in the South-eastern Anatolia, Turkey
Control / regulation	• equitable • flexible	• risk of water wastage • highly complex • skill required	• competent management • skill requirements • farmer organisations • hydraulic modelling	• electrically-operated upstream and downstream controllers are widely used • hydraulically-operated: AMIL – upstream control AVIS – downstream control (Alsthom 1980)
Pressure-governed	• efficient, flexible • water conservation • business enterprises	• rapid transients • highly complex	• competent management • skill requirements • modelling is essential tool • institutionalisation essential	• implemented as open and closed systems • implemented as upstream or downstream control
Composite commands	• any shortfall of a lower grade system can be improved by design	• hydraulically complex	• effective operations • enhancing the system during remodelling stages through learning from the past • must be compatible with the social context	• volume regulation can be implemented as strategic or a cascade of discrete local storage reservoirs • Warabandi in tertiary and upstream control in secondary canals • mixed control, developed by *Societe du Canal de Provence*, France, or AVIO by Alsthom (1980) • BIVAL developed by SOGREAH of France

description of the systems and their particular implementations. An insight into the issues associated with each of these classes of systems is presented in Table 2.

3.1 Storage-governed Canal Systems

In nearly-flat irrigation areas, source-water is not sufficiently higher than low-lying irrigation areas, so command is created by a provision of wide and long canals replenished at headwork and depleted at offtakes downstream. In reality, this is a hydraulic command method that is created by a small but significant water surface gradient where, hydraulic connectivity is continually maintained owing to in-channel storage. These canals are aligned along steepest gradients and this method can equally be called low inertial command. These systems can be inefficient for their slow response. The response times to variations in these systems are inevitably large. With an inherent slow response, this command method normally serves supply-driven implementations and therefore these systems are inflexible often suffering from poor equitability.

3.2 Hydraulically-governed Open-channel Systems

This command method is suitable for the contrivance of irrigation systems with mildly or steeply sloping terrain conditions. It is influenced by (*a*) gravity as the driving force (*b*) optimised canal sections (*c*) meandering canal alignments along gradually falling contour lines and (*d*) modification of gravity by friction, hydrostatic pressure and inertial forces as well as by some in-channel storage. Hydraulic structures along these dendritic canals comprise local over/under-shots and rudimentary offtakes. These systems are generally operated in steady state but owing to the lack of designed in-channel storage, transient/unsteady states created by offtakes, variable supplies and draining rainwater are dissipated naturally. Variations in supply or demand can hardly be transformed into system-wide hydraulic signals but instead "block inspectors" manage the system through manual operations. The systems in this class are supply-driven serving continuous or rotational deliveries and are normally inflexible.

Implementation examples of this command method are given in Table 2. The major brands include: (**i**) normal flow systems which are probably the remnants of prototype large-scale irrigation systems implemented in the 19th century; (**ii**) systems with proportional deliveries, see Burton, 1989; and (**iii**) **systems with flexible deliveries**, as implemented in the Sudan, Java and India.

3.3 Open-channel Inertia-governed Systems

Inertia-governed systems are generally suitable to deltaic landscapes with the command maintained by significant discharge gradients normally exerted by pumpage. These canals reach out remote areas outside the delta advancing along gently rising plains with the bed alignment of the canal along steepest gradients. In longitudinal profiles, the bed alignment may be seen as the opposite of the land gradient and the canal to appear as a cascade of pools with each pool elevated at its downstream end. Large low-lift pumps at the perching interfaces raise water from the low to the high elevation pool, see Fig. 3. When these operations are viewed in succession, each pool is seen replenished at the low-lying upstream and depleted by the elevated downstream pools. Level differentials at the front in this command method can be larger than those in storage-governed command. This command method is a technological product, which can be implemented as supply- or demand-driven systems.

The systems in this brand of command methods are more difficult to operate, as the in-channel storage ensures a continual hydraulic connectivity for rapid propagation of inertial disturbances upstream and downstream at the wave-speed, $c \approx \sqrt{gy}$. For y=1-m, then c>3-ms^{-1}, which is fast. Additionally, such a natural hydraulic connectivity in both upstream and downstream directions creates the risk of "hunting" between the pumps, adding to the complexity of their operations.

3.4 Open-channel Controlled/Regulated Systems

This command method marks the arrival of process-based open-channel hydraulics as an improvement over hydraulically-governed command. First implemented in the 1960s in the USA, these systems involve two innovations of (**i**) in-channel storage and (**ii**) regulatory structures with moveable units for controlling and maintaining target values of discharge or level through modulation. This new dimension in irrigation systems made efficiency and flexibility their performance criteria. Thus, many systems are remodelled worldwide with controlled hydraulic commands to perform as business enterprises.

Levels may be controlled using **upstream** or **downstream** control methods. An insight into these methods is obtained in terms of in-channel wedge storage within a pool. Ankum (1993) explains that there is "negative wedge" storage associated with upstream controls and "positive wedge" with downstream controls. As shown in Fig. 4*a*, "negative" signifies that the wedge is physically present in the pool but not readily available and this makes response times longer and slower. However, positive wedges, (Figure 4*b*), are readily available with short and fast response times but at the expense of costly level-top bank require-

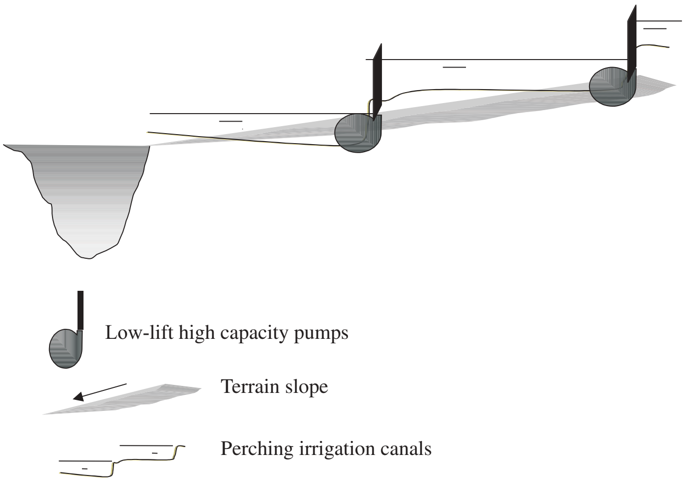


Fig. 3. Profile of of Storage-governed Irrigation Systems.

ments. Storage wedges ensure system-wide hydraulic connectivity for the propagation of hydraulic signals but the propagation in specific direction(s) is ensured by controller gates, detailed below.

Upstream control systems – Water levels within a pool under consideration change in response to fluctuations in demands and/or supply. Each pool has a controller gate upstream. The water level of the pool is only controlled by the downstream controller gate. The controller is associated with a deadband; it detects upstream level changes; and responds by modulating its gate openings if deviations from the target level are excessive. The controller will automatically take the gate to a new position by calculating the position for minimum deviations. In this way, excessive variations in upstream pools are transferred sequentially to downstream ones. This is tantamount to creating a one-way hydraulic connectivity in the direction from upstream to downstream. As a direct consequence, at high demands in upstream pools, their gates may have to restrict the flow towards downstream but increase the flow when demands fall. Thus, topend users are assured, in principle, of trouble-free services during surplus and deficit, leaving tailend users to struggle with shortage or flooding problems.

Downstream control systems – This is identical to upstream control except that the controller gate modulated to maintain its downstream levels. This results in (*a*) a hydraulic connectivity in the system for the transmission of hydraulic signals in the direction from downstream to upstream; and (*b*) level-top bank requirements for the pools. Hence, this creates a demand-driven capability, in which tailend gates dictate topend ones, even if topend pools have to lose the command for their own local users. Thus, tailend users are assured, in principle, of trouble-free services during surplus/deficit, but topend users are left to put up with the problems.

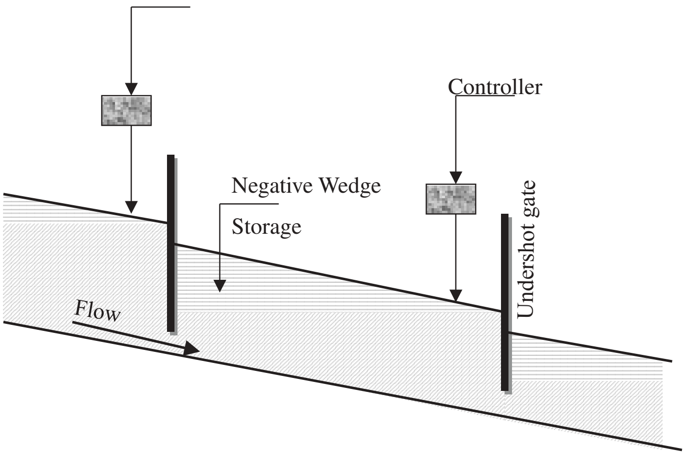


Fig. 4a. Upstream Control - depicting negative wedge storage.

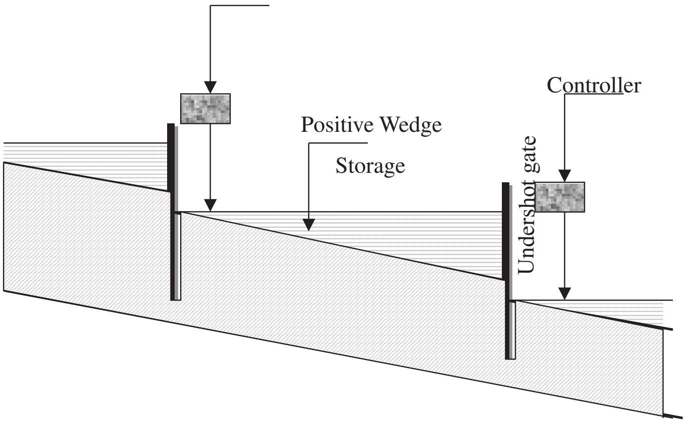


Fig. 4b. Downstream Control - depicting positive wedge storage.

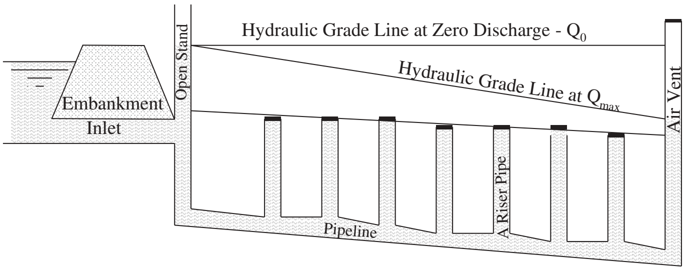


Fig. 5. Low-pressure Closed Systems.

3.5 Pressurised Closed Conduits

The development of these systems was epochal in water engineering and could be traced back to the 19th Century. Water from groundwater, reservoirs or canals enters the system by pressurisation using pumpage or gravity and is driven by pressure through mains, submains and lateral pipes of 0.2-1.5 m diameters with farm connections via riser pipes. Hydraulic integrity of these systems can be undermined if pockets of air are trapped and this partially depends on the reliability of source-water. For flat terrain layouts, pressure boosting is often needed with their water towers becoming land features. For ragged terrain layouts, a combination of pumping, break pressure tanks, cascading pipe diameters and tunnels may be employed. Pressurisation is potentially an ultimate solution against ragged terrain, shortest response times, high water conservation capabilities and least environmental impacts. However, these are at the cost of heavy investments, increased complexity, skilful operations and competent management. These systems are capable of random deliveries by the virtue of rapid response times and hydraulic connectivity, although the satisfaction of meeting random demand is not necessarily achieved and its achievement may even be counterproductive.

Pressure fluctuations in elastic pipelines propagate as pressure waves at sonic speeds. On this account, the paper recognises pressurisation as additional hydraulic command method. Pressure management is integral to this command method in terms of (**i**) identifying methods of aligning pipeline profiles with their surrounding topographies, (**ii**) maintaining operating pressures within their permissible ranges, (**iii**) ensuring system-wide hydraulic connectivity, and (**iv**) provision of elastic pipes for sonic propagation of hydraulic signals. Table 3 presents classification of irrigation systems in a matrix form with pressure management is laid out against different arrangements for pressure propagation. A closed system arrangement refers to systems not capable of internal resetting, which comprise one interconnected monolithic system. Otherwise, open systems refer to those being capa-

Table 3. Classification of Systems Under Pressurised Commands.

	Closed system	**Open system**
Low pressure	• Implemented as pipelines with 3-5 m pressure head • Suitable in gently sloping terrain conditions • Aligning the pipeline with the surroundings • often serving drip or subsurface applications	
	Low-pressure – closed systems see Fig. 5 • mainly upstream control • rather slow responding systems	**Low-pressure - open systems** • known as **semi-closed** (**Californian**) systems • downstream control by using float valves to maintain hydraulic connectivity from downstream to upstream, as in open-channels • widely used
High pressure	• suitable to uniform and mild slope terrain conditions with operating pressure heads under 30 m • solving the problem of aligning the pipeline with surrounding topography • cost-intensive • often serving sprinkler and on-farm applications	
	High-pressure - closed systems • inertia-governed systems with sonic hydraulic signals propagating upstream & downstream • complex transient hydraulics • random deliveries at the expense of costly advanced pressure controlled components • the Libyan Great Manmade River Project is grand example (see Kluth 1994), greatly exceeding conventional limitations • risks of operating pressures exceeding allowable pressure ratings in steep terrain	**High-pressure - open systems**, see Fig. 6 • operating pressures are maintained within permissible ranges using energy dissipater baffles • downstream control as in open-channels

ble of internal resettting, as they comprise or a series of subsystems filtering the propagation direction and retaining the one at the intended direction.

3.6 Composite Commands

The range of composite systems is vast and may be developed further to take advantage of innovations in the field of modern water-saving measures and provisions for suiting local conditions. The hydraulic components that can contribute to engineering composite systems include controls at bifurcation and offtakes, boosting the command by regulation or pumpage, and volume regulations. Composite methods can hydraulically be complex and their contrivance may stem from (*a*) management drives for effective operations or saving water and (*b*) learning from the past by enhancing the system during remodelling stages. The constituent composite commands must demonstrably be compatible. The compatibility of composite systems with the background social culture is another facet, as these contrived systems must not be divorced from their social context. Four examples are presented in Table 4 to illustrate the implementations of composite commands.

Table 4. Various Implementations of Composite Commands.

Method	**Main Features of the Particular Composite Command**
Volume regulation	• can solve effectively water-saving problems with significant fluctuations in flows • these regulations implemented by cascading storage reservoirs • widely used prior to 1960 before the availability of automatic controls and are still recognised for their effective water-saving potentials • may also be provided in association with level control facilities by a provision of in-channel storage capacities, as in mixed controls
Warabandi delivery with upstream control	• solves the inflexibility of proportional delivery systems • warabandi is well rooted in Pakistan • in remodelling the Patfeeder canal in the Baluchistan province, level regulations are implemented in the main and secondary (distributary) canals but minor canal deliveries are commanded on the warabandi principle using proportional diversion weirs
Mixed Control (see Fig. 7)	• solves equitability problems inherent in upstream and downstream controls • the solution comprises a cascade of main canal pools with upstream control at its top ends and downstream controls at tail ends and an intermediate pool having positive and negative storage wedges and a storage prism • the wedges maintain normal operations but the prism acts as a buffer for mismatches between topend and tailend deliveries
BIVAL	• solves the level-top bank requirements necessary for downstream control • first solution is at the expense of detecting water levels at more than one site within a pool, Ankum (1993) • automatically-operated gates maintain the wedge storage just sufficient to meet arranged-demands

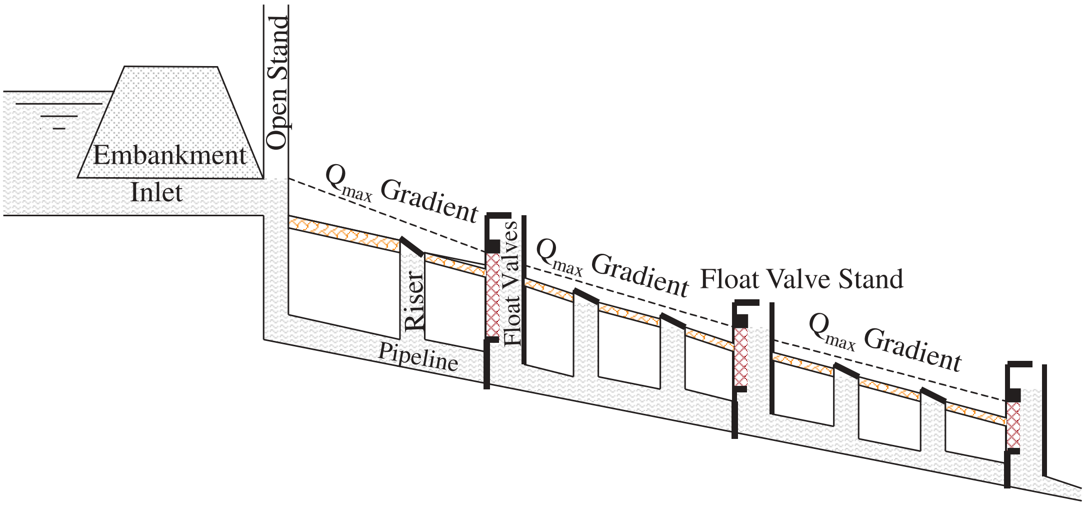


Fig. 6. Semi-open Systems with Float-valves.

4. Comments

The postulate on the key role of hydraulic command on classification and diversification of irrigation systems has been substantiated in this paper through citing and describing their international implementations. If one considers all other hydraulic factors, it is indeed remarkable that the minute differences in the properties of the characteristic direction(s) from one class of irrigation systems to another are responsible for the diversification of these systems. As a benefit of the postulate on classifying irrigation systems, a comparison of each class with one another invokes a tacit sense of incompatibility among them. This can now be explained by the differences in their inherent characteristic directions. A reflection of this is that irrigation engineers often replicate the same hydraulic command throughout the system and this explains the striking similarity among different parts of the same system, unless the system caters for composite commands. It also highlights the fact that an arbitrary combination of these commands in a single system will give rise to chaotic outcomes. It is not surprising that remodelling for bettering the whole of an old system is preferred to component retrofitting, as the latter is liable to mixing up commands thus encouraging spontaneity. An example of treating incompatibility is the provision of prism storage for creating buffer in mixed controlled systems. Two analogies are striking. (**i**) The role of characteristic directions in the diversification of irrigation systems is analogous to role of genes in the diversification of species. (**ii**) Incompatibility of a class of irrigation system associated with a certain command method with others associated with different command methods is analogous to no reproduction among different species.

Compatibility of engineered irrigation systems with their social context is well acknowledged but this is difficult to quantify. One solution is suggested here as a further application of the classification method. Consider appraising the contribution of farmers (users) and professional bodies for the business performance of two typical irrigation systems: downstream-controlled and hydraulically-governed. The hydraulics-related management issues of these systems are outlined in Fig. 8, Template 4, which also depicts their correspondence to the physical subdivision of these systems. Taking hydraulic complexity in terms of underlying processes and their interactions, it is possible to associate them with

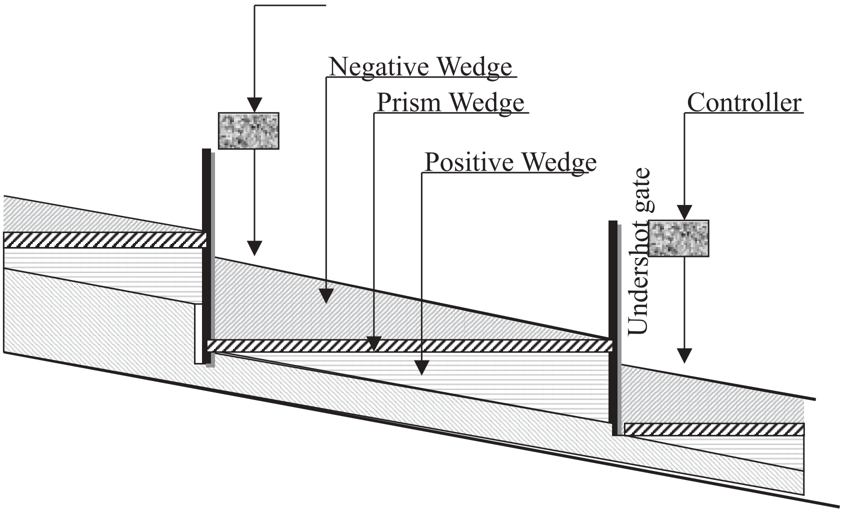


Fig. 7. Downstream Control - depicting positive wedge storage.

Figure 8*a* Downstream Controlled Irrigation System

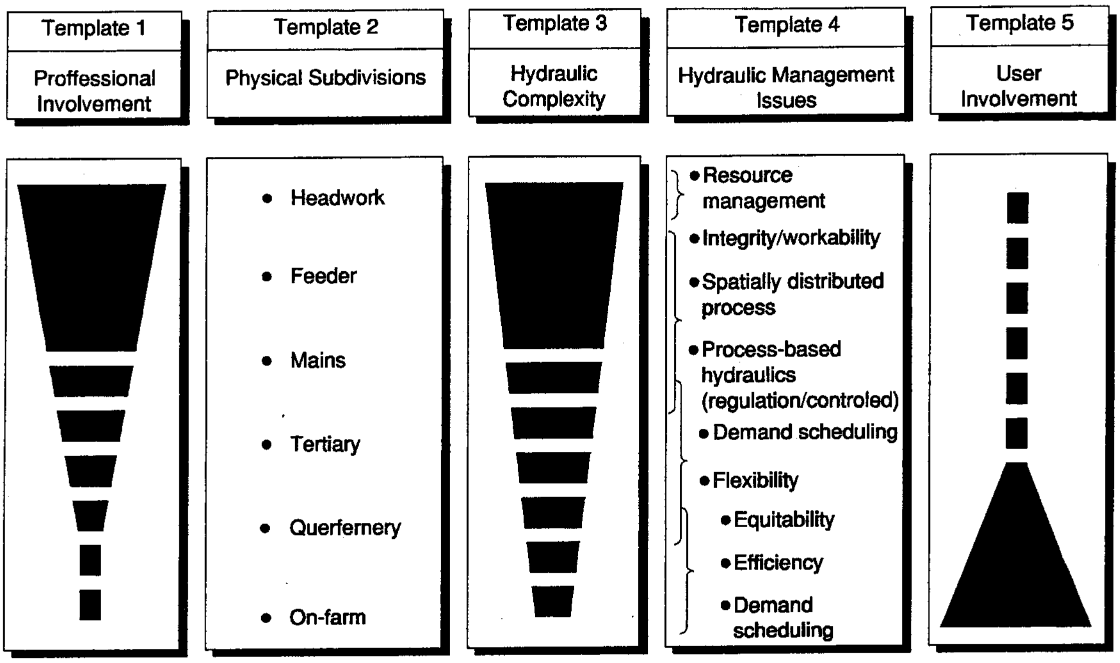
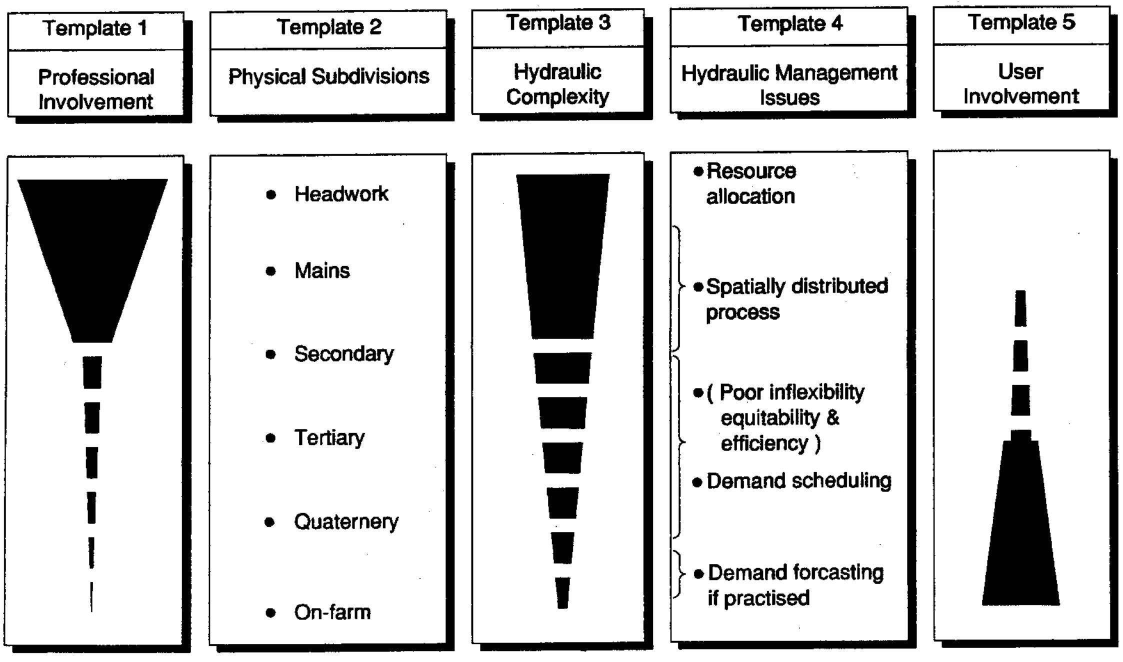


Figure 8*b* Hydraulically-governed Irrigation System



a weighting value. Fuzzy logic may then be used to quantify their complexity but since specific project data is not being used in this paper, indicative representation is adopted and this is depicted in Template 3. Similarly, Template 1 and 5 depict an indicative representation of the involvement of professional bodies and farmers for ensuring steady performance of these systems as business enterprises.

The above approach suggests a quantitative framework for comparing irrigation systems and integrating knowledge gained from their problem-solving incorporating both technical and social dimensions. Fig. 8 reveals variability patterns (**i**) in a system, (**ii**) in systems associated with a hydraulic command method and (**iii**) in systems across the various classes. This framework can evidently facilitate quantitative measurement of compatibility between technical and social complexities. The approach reveals the intensity with which institutionalized professional bodies are required for problem-solving, which is higher in relation to downstream-controlled systems than hydraulically-governed ones but both tend to reduce in the downstream direction. As expected, user involvement depends on the location of hydraulic complexities.

The mathematical basis of characteristic directions was described by (1) – (5). Some of the new possibilities of upstream, downstream or mixed control methods were created by filtering and retaining the propagation of disturbances only in the intended direction(s) using process-based hydraulics. Other command methods may be feasible. A notable example is the use of the siphon effect to lift and convey water. Indeed this is widely used at farm outlets but the author is not aware of its use in irrigation systems as a form of hydraulic command at large scale. The reason is that irrigation systems are often subjected to varying demand and supply but siphons require steady reservoir levels both at its inlet and outlet sides, else tedious priming operations will ensue. Another possibility is pressurised command methods using rigid pipes, allowing hydraulic disturbances to propagate as mass oscillations. The author is not aware of such a system, although prototype pressurised irrigation systems can fall into this class. Another possibility is to develop a command method based on "diffusion analogy," which is a development on the kinematic characteristic direction allowing the wave shapes to change. The author is not also aware of any irrigation system implemented on such a command method. Thus, it seems that other command methods are neither engineered nor likely on mathematical grounds. This leads to a tentative conclusion that a great majority of internationally implemented irrigation systems have been included in the classification method presented in this paper.

5. Conclusion

This paper classifies irrigation systems by substantiating the postulate that hydraulic command is responsible for their generic variations. The term hydraulic command is used in this paper in a context wider than its conventional connotation. Through this term the paper articulates irrigation engineers' intuition that, unlike river drainage systems with spontaneous gravity flows, the conveyance of source-water to farms in irrigation systems has to be engineered throughout. The provisions of gravitation and/or pressurisation to drive water are only the first step to create command. The term also creates the sense that command is maintained intrinsically throughout space and time within irrigation systems by contributions of (*a*) channel geometry, (*b*) alignment of the conveyance channels (*c*) a host of hydraulic/control complexes, and (*d*) interactions with social context. When all these factors are put together, a picture emerges that countless irrigation systems worldwide can be classified into classes according to their hydraulic command methods, as follows:

1. Hydraulic disturbances propagate at the celerity of shallow water wave speed in canals or at sonic speeds in pressurised elastic pipeline systems.
2. Hydraulic disturbances lend to mathematical descriptions of the method of characteristics. Three hydraulic command methods were recognised. (**i**) Storage-governed command follows the kinematic characteristic direction. (**ii**) Hydraulically-governed command follows hydrodynamic flow conditions. (**iii**) Inertia-governed command is created when sharp fronts can be developed in the presence of significant in-channel storage. These command methods are widely used in irrigation canals but their equivalent can also be found in pressurised irrigation systems.
3. The direction of propagation of hydraulic disturbances can be controlled and regulated by the provision of process control technology to transform such disturbances into detectable hydraulic signals. These lead to upstream/downstream control command methods in canal/pressurised irrigation systems.
4. The paper also presented examples of composite command methods including mixed controls.

The paper shows that each command method represents a class of irrigation systems and the systems associated with a class share the same command method and display similar generic complexities. Thus, it becomes possible to identify the synergistic virtues and shortfalls associated with these systems by providing a clear focus on hydraulics-related technical and management issues and to gain an insight into differential variations from one class of systems to another. This provides a tentative approach for integrating knowledge and assessing the compatibility of technical and social complexities of irrigation systems. The contribution of this paper is methodological and does not present any new hydraulic command method. This method of classification can be used in comparing different irrigation systems with one another and for quantifying the technical compatibility of a system with its social context.

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