OPERATION-BASED DESIGN GUIDELINES FOR MODERN IRRIGATION DELIVERY SYSTEMS

David C. Rogers[1] Shane Lindstrom[2]

O. Duane Mallicoat[3]

ABSTRACT

The Gila River Indian Community (GRIC) of central Arizona is developing the Pima-Maricopa Irrigation Project (P-MIP) to deliver irrigation water to over 146,000 acres (59,000 hectares) of farmland. Included in the P-MIP will be the primary, secondary and tertiary delivery systems. Surface irrigation is extensively practiced on the GRIC and is expected to remain the predominate form of on-farm irrigation. In order to meet high standards for on-farm water use efficiency, the project must be able to provide a flexible and dependable supply to the water users, and the main conveyance system must be designed for the flow changes that can result from these flexible deliveries. Four independent engineering firms have been contracted to design the project's main delivery canals, pipelines, and related structures. Therefore, to ensure a final product that is consistent with project goals, project engineers had to develop design guidelines for these firms to follow. Water conveyance system design criteria were based on anticipated project operations. Maximum flows and maximum anticipated flow changes were projected for farm turnouts, then for the laterals that serve those turnouts, and finally for the main canals. Modern canal operations require a design that is based on a *maximum rate of flow change* criteria in addition to the traditional maximum capacity criteria. The biggest challenge was to quantify allowable operating conditions — such as the amount of scheduled and unscheduled flow change per day — so structural features could be designed to accommodate these operations without exceeding structural constraints. This paper presents guidelines that can be used by irrigation project designers to yield a canal system capable of efficient operations and flexible delivery to water users.

INTRODUCTION

[1] Hydraulic Engineer, U.S. Bureau of Reclamation, Water Resources Research Laboratory, P.O.Box 25007, Denver CO 80225-0007, (drogers@do.usbr.gov)

[2] Water Management Engineer, Pima-Maricopa Irrigation Project, P.O.Box E, Sacaton AZ 85247, (slindstr@gilariver.com)

[3] Consulting Engineer, Mallicoat Engineering, 2045 Heitz Road, Jacksonville IL 62650, (dmalli@csj.net)

The Gila River Indian Reservation is located in Central Arizona just south of the Phoenix metropolitan area. The reservation occupies 372,000 acres (150,000 ha) of the Gila River valley, where the GRIC uses Central Arizona Project water, groundwater, and water from the Salt River and Gila River to irrigate cotton, small grains, alfalfa, citrus, olives, and small acreages of specialty crops.

Water use and water conveyance efficiency goals for the P-MIP are quite high. The field efficiency goal is 78 per cent and the distribution efficiency goal is 95 per cent. (This means that 78% of the water delivered to farms is used beneficially for crop production and 95% of the water entering the conveyance system reaches the farms. Canal seepage, evaporation, and spills should be less than 5% of total flow.) In order to attain these goals, the water delivery system must provide flexible, accurate deliveries with very little waste. The delivery system will need to be demand-oriented and the conveyance facilities should be sized and designed based on anticipated operation and patterns of delivery flows.

To expedite development, the project has been split into four geographic areas and the primary delivery system has been divided into four segments. Four independent engineering firms have been contracted to design the project's main delivery canals, pipelines, and related structures. To ensure that the multiple design contracts yield a consistent and appropriate end product, the P-MIP engineering staff has developed project design guidelines for the firms to use. These guidelines are based on anticipated project operations in order to produce a final design that will allow operators to achieve project efficiency goals.

Design guidelines needed to address major issues such as delivery system size, allowable water levels, regulatory storage requirements, and control capabilities. The most difficult part of this process is to quantify operating criteria for such things as operational flexibility. Guidelines must provide the design engineering contractors with criteria that are specific enough to be useful, yet not overly restrictive. Ultimately, the responsibility still lies with the design engineer to evaluate alternatives and to produce the most technically and economically feasible design.

Traditionally, the size of conveyance and control structures has been based on a maximum flow capacity, sometimes called the "design" capacity. Although maximum flow capacity is still an important criteria, modern water delivery projects like P-MIP should also be designed for flow changes. Flow changes affect the size and design of conveyance channels, control structures, turnout structures, and the control system. Both scheduled and unscheduled flow changes need to be evaluated. In addition to establishing design criteria, these quantities will provide operating guidelines for future use. Design guidelines will provide a record of the operations for which the project has been designed. In the future, this information can be used to establish operating rules for water users and operating personnel to follow.

The design guidelines developed for the P-MIP provide an example for other modern irrigation projects. Although some of the details are project specific, similar operations-based priorities should apply to other new water delivery projects.

DELIVERY SYSTEM SIZING

The process to size water conveyance and control features should begin with farm operations and work from the downstream ends of the delivery system towards the upstream supply source. Traditionally, sizing of distribution systems was based on a maximum flow requirement computed from the peak period crop water requirements with allowances for losses from seepage, evaporation, and operational wastes. This traditional approach provides adequate capacity for a project with rigid delivery schedules, but it is inadequate for modern canal operations with flexible deliveries. For flexible operations, sizing should be based on *flow changes* as well as peak flow capacities. Maximum flows and maximum anticipated flow changes should be projected for farm turnouts, then for the individual laterals that serve those turnouts, and finally for the main conveyance canals and pipelines. Not all design criteria can be finalized in advance of project design; designers must continue to establish and refine criteria throughout the design process in coordination with the design of project features.

Flexibility Factors

Flexibility is defined as water deliveries that can vary in frequency, rate, and duration. The irrigation supply to the farm should facilitate and not restrict the total farm management program (Merriam, 1991). Restraints on frequency, rate, and duration – which may appear to simplify project operations and cost – significantly affect the farmer, compromising total farm management.

The flexibility factor is a practical consideration that is generally applied to surface irrigation (Savage, et al, 1987). Flexibility factor is a multiplier that increases conveyance and turnout capacity above the calculated design flow. For the P-MIP, the flexibility factor is defined as the actual capacity divided by the minimum (continuous flow) capacity. Flexibility factors should be larger near the downstream ends of the conveyance system to prevent the restrictions of a rotation delivery schedule (Clemmens, 1986).

On-farm Requirements

The type and location of each farm turnout should be based on irrigation needs rather than delivery system needs. For surface irrigation to be efficient, the farmer must be able to respond to constantly changing crop and soil requirements and not compromise farm management in order to conform to water delivery system constraints. Important irrigation criteria are the turnout flow rate, the ability to maintain steady flow, and convenience for farmers.

Delivery system size and flow rate should be based on the predominant or projected on-farm irrigation methods. Planners must estimate water requirements by combining soil and weather data with projected cropping patterns, farm size, and irrigation practices. On-farm requirements should be used to define the seasonal water allotment, the delivery flow rate, the frequency and duration of water delivery to each farm, and the level of restriction to turn on and off each farm delivery. The key is for the system to have enough flexibility so as not to restrict cropping patterns or modern irrigation technology. As stated by Clemmens (1987), "Limiting the delivery flow rate during design can have a significant impact on future irrigation practices."

After consultation with USDA-Water Conservation Laboratory in Phoenix, Arizona, the delivery flow rate was chosen to be 15 ft^3/s (425 l/s) to each delivery unit. While larger delivery flow rates were discussed, it was felt that 15 ft^3/s was an economical choice that ensures the viability of highly efficient surface irrigation methods. At some locations, smaller flows may be delivered to fields that use other irrigation methods.

Another important design criterion is the hydraulic grade line elevation required at each field. Maximum and minimum delivery water surface elevations must be established in order to design the conveyance system and turnout structures. At P-MIP, field delivery water surface elevation will be at least 1 ft (30 cm) above the highest elevation in the fields being served.

Water Delivery Through Canal Turnouts

System operations should be based on a prescribed level of delivery flexibility, as characterized by the water scheduling rules. It is assumed that the P-MIP will use a *Limited Rate Arranged* delivery schedule. An important factor to be determined is the water order advance time required before delivery flows can be turned on and off. For P-MIP, the goal is a 24-hour or less advance time for water orders. However, unrestricted early shutoff is to be allowed. Irrigators will be able to shut off their delivery flow at any time, without prior notification. The water conveyance system is to be designed for 90 percent service level, i.e., when requested, water will be available 90 percent of the time. The 10 percent when water requests cannot be met should cover unusual events that cause many irrigators to request water at the same time, e.g., following a rainstorm or other shutdown period.

Another factor deals with the level of rotation expected within each delivery area. For P-MIP criteria, it was assumed (but not required) that large, contiguous farms will use an internal flow rotation, resulting in a relatively continuous flow from the delivery system. Discontiguous units will probably not use internal rotation, resulting in higher turnout flow variation. During peak-use periods, and for the smallest farm units (10-acre parcels), an imposed rotation delivery could be implemented by the irrigation district if necessary.

Flow Capacities for Canals and Laterals

As described by Clemmens (1987), sizing criteria should be a function of location within the delivery system, type of delivery schedule, and on-farm irrigation methods. Location within the system is better defined by using the land area served than by using the number of turnouts served, because different turnouts will have different characteristics. (Some may rotate a steady turnout flow to several fields while others may turn on and off.) This allows sizing criteria to be evaluated using a concept of relative service area (A_n) and relative flow (Q_n), defined as follows:

$$A_n = \frac{A}{A_t}$$

where: A = total downstream land area served
A_t = land area within a theoretical rotation area

$$Q_n = \frac{Q}{Q_t}$$

where: Q = flow rate in the conveyance system
Q_t = flow rate to each delivery unit

The Gila River Indian Community adopted a Master Plan for Land and Water in 1985 that estimated a peak use of .37 inches (1 cm) per day using a projected cropping pattern based on an economic evaluation. With this projected water use, a 78 percent on-farm efficiency, and a 15 ft^3/s deliverable flow rate, a theoretical area of about 750 acres (300 ha) could be irrigated per day. For the P-MIP, the theoretical rotation area is projected to be 900 acres (360 ha) to allow for effects due to net farmable acreage reductions and fallow land.

A_n and Q_n can be used to quantify the flow rate (Q) at each point in the conveyance system. For a continuous flow system, $Q_n = A_n$. For arranged delivery schedules, Clemmens recommends the following relationships between A_n and Q_n:

$$Q_n = A_n + 1.6$$

Because shutoffs will be unrestricted at P-MIP turnouts, P-MIP increased the capacity slightly from the Clemmens recommendations to the following:

$$Q_n = 1.1 * A_n + 1.8$$

Using the prescribed values $A_t = 900$ acres and $Q_t = 15$ ft³/s, this equation becomes:

$$Q = 15 * [1.1 * (\text{acres}/900) + 1.8]$$

or

$$Q = \text{acres}/54.5 + 27$$

This equation provides a flexibility factor that equals 1.8 at the tail end (as the area served approaches zero) and approaches 1.1 at the head end.

Analysis of the above equation revealed it worked well for intermediate acreages, but it did not deal sufficiently with either the tail end of laterals or for a large service area (e.g., the maximum flow capacity at the head of the system). The questions that remained were:

1) how to size canals and laterals when the actual service area falls below the theoretical rotation area (< 900 acres), and
2) how to size the main canal and large laterals for large service areas (>5,000 acres).

For small service areas (rounded to <1000 acres), it makes sense for lateral capacity to be a multiple of the delivery flow rate. Flexibility factor should increase as the service area reduces in size, in order to accommodate the probability that two farmers may want water simultaneously. For true flexibility, these guidelines tried to avoid the old farming adage, "You're married to your neighbor."

The following guidelines were used for smaller lateral capacities:

10 - 125 acres	-	15 ft³/s
126 - 550 acres	-	30 ft³/s
551 - 1,000 acres	-	45 ft³/s

Minimum capacity for areas greater than 10,000 acres will be estimated using Clemmens' equation:

$$\mathbf{Q_n = A_n + 1.6}$$

which converges toward:

$$\mathbf{Q = acres/60}$$

As a transition between large and intermediate service areas, a straight line fit between the two above equations will be used for areas between 5,000 and 10,000 acres:

$$\mathbf{Q = acres/104 + 71}$$

The above equations and guidelines offer a convenient method to estimate canal and lateral sizes during design planning, but final design should be based on specific engineering and economic analyses. While this is suitable for preliminary planning and design, future guidelines will attempt to further differentiate between the main stem and the lateral systems. Depending on the distribution and types of turnouts, some laterals may need to be enlarged or reduced further to accommodate flow changes or expected on-farm practices.

FLOW CHANGES

Maximum rate of flow change is an important design criterion for canals. Flow changes should be projected by evaluating when turnouts are expected or allowed to start and stop taking water. As with flow capacities, flow changes in individual laterals or branch canals will be additive to produce a total flow change for the main canal upstream. During normal operations, negative flow changes at some turnouts or laterals will offset positive flow changes in others. Design criteria should be based on abnormal operations when the maximum net positive or negative flow change can occur. Abnormal operations might include early shutoff of numerous farm turnouts or the large-scale startup that follows a low-flow period.

For design purposes, projected flow changes must be quantified so designers can use numerical quantities. Standardized flow-change criteria do not exist, so the criteria used on this project were based on experience and proactive reasoning. Two types of flow changes should be considered: *scheduled* (those that are known in advance) and *unscheduled* (those not known until after they occur).

Scheduled Flow Changes

For flow changes that are known in advance, system operations should be able to prevent significant imbalances between supply and demand. Even when system inflows and outflows remain balanced, however, water levels throughout the canal system must change when the flow rate changes. In order to design the conveyance features (canals, check structures, and turnouts), the amount of scheduled flow change must be quantified.

Assuming a 5-day irrigation frequency, 20 percent of the farm deliveries could turn on and off each day. In a rotation delivery system, the startups would balance the shutoffs, resulting in very little net flow change in the conveyance system. At P-MIP, increased delivery flexibility will allow an imbalance between daily startups and shutoffs. For design purposes, it is assumed that flow in a lateral could vary by as much as 20 percent of the lateral capacity in a 24-hour period. Laterals and turnouts must be designed for the water level variations that would accompany this 20 percent daily flow change.

Flow changes in the main canal system will depend on the size and location of regulatory storage reservoirs. In canal segments upstream from regulatory storage, flow changes should be relatively minor. These canal segments should still be designed for unsteady flow, but the rate of flow change should be much smaller than for canals and laterals that must respond directly to turnout changes. Upstream segments of the main canal system should be designed in coordination with storage reservoir design; the maximum rate of flow change will depend on reservoir size.

Main canal and secondary canal segments downstream from storage reservoirs should be designed to accommodate a flow change equal to 20 percent of design flow capacity in a 24-hour period. This criterion is consistent with lateral design criteria, based on the assumption that 20 percent of deliveries could turn on or off in one day. If the system is designed using this criterion, more severe reductions in demand flow (>20% Q_{max}) would result in spills through wasteways. Delivery flow increases would need to be restricted (arranged) so main canal flow doesn't increase by more than 20% Q_{max} in one day.

Unscheduled Flow Changes

All irrigation canals experience unscheduled flow changes, where actual deliveries differ from predicted values. On a project that provides a high level of delivery flexibility, a significant amount of unscheduled flow change can occur. An important factor at P-MIP is the plan to allow unrestricted early shutoff at deliveries. To accommodate unscheduled flow changes, the P-MIP conveyance system is being designed to manage a 10 percent flow discrepancy without wasting water or shorting scheduled turnout deliveries. This means that actual deliveries can differ from the scheduled deliveries by as much as 10 percent of the total delivery capacity.

Because the four segments of the P-MIP are being designed by different engineering firms, each design segment (i.e. reach) of the canal is to be self-sufficient in its capability to withstand unscheduled flow changes. For each reach, the total delivery capacity is defined as the difference between conveyance capacity at the reach's upstream end and the capacity at the reach's downstream end. The 10 percent unscheduled flow mismatch must be stored (if it is an excess), supplied (if it is a shortage), or otherwise offset by equal and opposite flows into or out of the reach (such as groundwater pump inflow changes) that do not result in waste.

STORAGE

Delay Times

Compensation for unscheduled flow mismatches must be provided for a duration of time until an appropriate flow adjustment from the system's headworks arrives at the site. At P-MIP, the quickest source of main supply flow adjustments will be the Central Arizona Project (CAP) turnout to the P-MIP system. Normally, changes to this flow require 24-hours' notice. Additionally, the arrival of supply flow adjustments will be delayed by the transit time to the site. Transit time is influenced by the open channel celerity (translatory wave travel velocity), by the volumetric (storage) changes that will accompany flow changes in canal pools, and by intermediate check gate control.

For example, a supply flow increase will create a translatory wave that travels downstream through the canal system. The leading edge of this wave travels at a speed equal to the celerity plus the flow velocity. However, some of the extra water from this flow increase remains behind to fill up the canal, because the canal must flow at a greater depth in order to pass the increased flow. The new (increased) flow cannot be fully established until this filling is complete. Reach 2 will not receive the full flow change until Reach 1 has been filled to the new flow level.

During a maximum unscheduled flow change event, the flow at any point in the conveyance system could change by 10 percent of that segment's design capacity. This assumes that all delivery flows in the P-MIP system change by 10 percent. The maximum in-channel volume change occurs when the flow changes from 90 to 100 percent of capacity in each segment. In Reach 1, this requires a total in-channel volume change of 2.8 million cubic feet of water. It will take approximately 4 hours for the extra water entering Reach 1 to fill this volume. Therefore, Reach 1 must be able to absorb unscheduled flow changes for 28 hours (24-hour CAP turnout delay plus 4-hour Reach 1 volume delay).

In Reach 2, a change from 90 to 100 percent flow requires a total in-channel volume change of 1.1 million cubic feet of water. It will take 3.5 hours for the extra water entering Reach 2 to fill this volume. Reach 2 must be able to absorb unscheduled flow changes for 31.5 hours (28-hour Reach 1 delay plus 3.5-hour Reach 2 volume delay).

<u>Volumes</u>

The maximum conveyance capacity in Reach 1 is 2400 ft^3/s at the upstream end and 1150 ft^3/s at the downstream end, so the total delivery capacity from Reach 1 is 1250 ft^3/s. For design purposes, the maximum unscheduled delivery flow change is 125 ft^3/s (10% of 1250 ft^3/s). If no other method exists to offset this flow change until a change in the main supply flow arrives, the volume of storage required for Reach 1 equals:

$$(125\ ft^3/s) \times (28\ hours) = 12{,}600{,}000\ ft^3 = 289\ acre\text{-}ft$$

The total delivery capacity from Reach 2 is 450 ft^3/s (1150 ft^3/s - 700 ft^3/s), so the maximum unscheduled delivery flow change is 45 ft^3/s. If no other method exists to offset this flow change until a change in the main supply flow arrives, the volume of storage required for Reach 2 equals:

$$(45\ ft^3/s) \times (31.5\ hours) = 5{,}100{,}000\ ft^3 = 117\ acre\text{-}ft$$

These volumes can be reduced if the unscheduled delivery flow change can be compensated by changes in well-pump inflows or other flow diversions. Some of the remaining volume could be supplied by in-channel storage, if canals and structures are designed to permit water level variation. For example, a 12-inch rise in the canal water levels equals a 125 acre-ft storage change in Reach 1 and a 68 acre-ft storage change in Reach 2. If in-channel storage is to be used in this way, the conveyance system (e.g. canals, check structures, turnout structures, bridges) must be designed accordingly.

OTHER DESIGN CRITERIA

Water Level Range

The range of water levels within a canal or lateral will be limited by the minimum water conveyance depth, by the lining and bank freeboard, and by the design and location of turnouts. At high flows, the minimum level required for conveyance must be maintained during all operations. Depth fluctuations and volume changes accompanying flow changes must not drop the canal water surface below this minimum level. Additionally, minimum water levels should be established throughout the canal and lateral system to assure adequate delivery of flow through lateral head gates and turnout gates. Canals and laterals should have enough check structures to maintain this minimum water level at low flows. At P-MIP, design criteria required that each turnout must be able to deliver it's full design flow for any canal flow (Q) in the range:

$$20\%\ Q_{max} \leq Q \leq Q_{max}$$

where Q_{max} is the maximum capacity (i.e. design capacity) of the canal or lateral supplying that turnout. In other words, the conveyance system must be able to deliver water to any turnout unless the system is flowing at less than 20 percent of capacity.

Modern canal operating methods often include the use of in-channel storage to increase delivery flexibility and reduce waste. Therefore, maximum canal water levels may exceed the full-flow normal depth. To establish maximum water level profiles, operational flow changes need to be studied to compute the water volume changes and the resulting depth changes. Then, canals should be designed with adequate freeboard above the maximum water levels.

Water Level Fluctuation

A maximum rate of change in canal water levels should be established in order to prevent lining damage from rapid drawdown of the water surface in canals and laterals. As a general rule for lined canals, the rate of water level drawdown should not exceed 6 inches (15 cm) per hour or 12 inches (30 cm) in 24 hours. A higher rate of drawdown may be acceptable where the canal is specifically designed to withstand rapid drawdown. For example, some canals have reinforced lining or under drainage that allows more rapid drawdown (e.g. 18 inches in 24 hours) without damaging the canal lining. Many small laterals (ditches) can be dewatered rapidly without damage.

Another reason to limit water level fluctuations is to provide steady flows into branch canals and farm turnouts. Too much fluctuation in the canal water level will create undesirable flow changes through lateral head gates and turnout gates. Designers must establish acceptable water level fluctuations at turnouts in concert with turnout and distribution system design. It is recommended that acceptable turnout flow fluctuations be established first, then turnouts and laterals be designed accordingly.

Turnout Design

Turnouts should be sized large enough to deliver their design flow at the minimum available head, with adjustability for higher heads. Manually-controlled gravity turnouts (e.g. undershot gates) require a steady control water surface in the lateral. First, designers should establish the acceptable amount of flow fluctuation during an irrigation period. (During a single turnout gate set, say 24 hours.) This criterion should be based on type of irrigation and service expectations. Then, the corresponding amount of head variation should be computed for each turnout. If lateral water levels will fluctuate more than the established tolerance, alternate turnout designs should be used. Possible alternatives include baffled constant-flow turnouts and automatically-controlled turnout gates.

As part of the design process, the following design criteria should be established for turnouts:

- design flow capacity
- allowable flow fluctuation during a single gate set
- maximum range for control water surface (lateral water level at turnout location)
- allowable control water surface fluctuation during a single gate set

Design details for several traditional types of turnouts are provided in the book *Design of Small Canal Structures* (Aisenbrey, 1974).

Lateral Design

As stated above, lateral design must be coordinated with turnout design to assure that turnout flow criteria are met. Significant criteria for lateral design include:

- meet control water surface range criteria at each turnout
- meet water level fluctuation criteria at turnouts
- seepage criteria
- right-of-way considerations

Designers will need to establish technical and economic feasibility of alternative lateral designs. Design alternatives should include:

- conventional open canals
- level-bank canals
- pipelines

Conventional canals may not be able to meet turnout flow criteria in areas where numerous independent turnouts can create large, uncoordinated flow changes. Level-bank canals may be warranted in these areas. Level-bank canals can respond much better to demand changes than conventionally-designed canals, increasing delivery flexibility for a moderate increase in cost. Pipelines will provide the most delivery flexibility. Buried pipe also has advantages over canals in regards to safety, right-of-way requirements, and access to fields. However, the initial cost for pipelines is much greater than for canals. Pipeline laterals are most feasible when there is a substantial elevation drop from the main canal to the fields, which decreases the required pipe diameter.

For open laterals, check structures should be located so as to assure an adequate control water surface for all turnouts. Some check structure locations will be determined by natural terrain features such as elevation drops or gullies. Drop structures or inverted siphons at these locations will probably require a check inlet. The distance (and the lateral's vertical drop) between checks should be small enough so that flow changes will not cause excessive depth fluctuations. For example, if a lateral is being designed for a 20% flow change per day and the maximum allowable depth fluctuation is 12 inches (30 cm) per day, then check structures should be spaced closely enough so a 20% flow change does not create more than a 12-inch change in water level anywhere in the lateral. Steady-state backwater curves (gradually-varied flow profiles) can be used to compute the appropriate check spacing.

Main Canal Design

Typically, canal structures should be designed to prevent exceeding the water level criteria mentioned above. As an alternative to preventing excess water level fluctuations, canal segments can be designed with under-drainage systems or reinforced-concrete lining to allow greater canal water level fluctuations. Check structures should be located so as to assure an adequate control water surface for all lateral head gates and turnouts, and to permit operational flow changes without exceeding water level criteria. Main canal check structure location and spacing criteria should be equivalent to the criteria for laterals.

Check structures should be designed for the planned method of pool operation. For example, if canal operations will increase water level above the normal depth for maximum steady flow, check structures must be able to contain and control this higher water level. (If the check contains overflow weirs, the weir crest must be raised.) Check structures also must be designed with gates, hoists, motors, and power systems consistent with supervisory control requirements.

CONTROL STRATEGIES

Laterals

For open laterals, the method used to control check gates will depend on:

- lateral size
- distribution and coordination of turnout flow changes
- sensitivity of turnouts to lateral water surface fluctuations
- pool operating method
- anticipated ditchride frequency to adjust check gates and turnouts

Automatic control will be most appropriate and beneficial for laterals where:

- the lateral is relatively large, serving a large area with numerous turnouts
- random turnout flow changes will create frequent flow changes in the lateral
- the tolerance for water level fluctuations is small
- a level-bank method of pool operation is to be used
- a ditchrider cannot visit check sites frequently enough to keep up with flow changes

Local manual control may be more appropriate where:

- the lateral is relatively small and manageable for a ditchrider
- turnout flow changes will be coordinated or rotated to minimize flow changes in the lateral
- turnouts are not sensitive to water level fluctuations (e.g. serving pipe distribution systems with outlet control)
- a constant downstream depth method of pool operation is used
- a ditchrider will be on site to make all turnout flow changes and can adjust lateral gates while adjusting turnouts

In laterals or portions of laterals that are upstream from a reservoir or another channel, supply-oriented operation is recommended. This is a conventional operating concept where flow changes are routed downstream from the lateral head gate towards the tail end. Upstream control is used at check gates to maintain a constant water level upstream from each check. Overshot gates, or undershot gates with bypass weirs to pass excess flows, are recommended for this type of operation. Supply flow should always be greater than or equal to the demand, with excess flows at the tail end diverted into storage or to another canal.

Where there is no downstream storage to accept excess flows, laterals should be designed for demand-oriented operations that will respond to demand changes rather than to supply changes. Check gates should be controlled based on downstream needs, with control adjustments migrating from the tail end towards the lateral head gate. A good design for this situation is a level-bank lateral with gates that automatically maintain the downstream water level. Either float-operated gates like the French AVIS gate or motor-operated undershot gates with microprocessor control could be used.

Whatever methods of operation and control are used, designers will need to assure consistency within each lateral. Different methods should not be mixed within an area unless a reservoir separates the different segments.

Main Canal

The main canal system should have enough control flexibility so canal operators can manage all flow changes without exceeding design and operating criteria. Because of the system's size and the significant flow changes anticipated, a supervisory control system is highly recommended for the main canal system. Operators should be able to monitor canal water levels and gate positions throughout the system from a central control headquarters, or master station (remote monitoring). They should also be able to adjust main canal check gates from the master station (remote control).

A fixed, inflexible control system -- such as float-operated gates -- is not recommended for the main canal. This type of a control scheme may be appropriate for laterals, but it will not provide adequate flexibility for the main canal system. Canal operators must be given the capability to adjust canal operations for varying conditions in the future. Local automatic water level control may be beneficial at some main canal check structures, but only as a part of a supervisory control system that allows operators to override local controllers with global strategies. Similar to cruise-control in an automobile, local controllers may be useful to maintain water levels at some sites when conditions are relatively steady. However, local control will not be effective for managing large flow changes. Supervisory control will be the most effective method to manage in-channel storage volumes when significant changes occur.

[redacted]

SUMMARY OF RECOMMENDATIONS

The operations-based design guidelines developed for the P-MIP could serve as an example for other modern irrigation canal projects. Some key recommendations are:

- Turnouts should have enough capacity to permit on-farm flexibility. Turnout design flow capacity should be twice the flow rate required for a continuous flow system.

- Laterals should be able to respond to changes in downstream demand with a minimum of operator intervention. Where it is desirable for lateral flow to automatically keep up with turnout flow changes, pipe laterals could be used or open laterals could be designed for level-bank operation with automatic downstream control gates. Deliveries will still need to be arranged to prevent flows that exceed lateral capabilities, but no operator intervention will be required for early shutoffs.

- The delivery system should be designed for flow changes. Daily scheduled flow changes of up to 20 percent of delivery capacity and unscheduled flow changes of up to 10 percent of delivery capacity should not create waste or other significant operating problems. A combination of groundwater pump adjustments, in-channel storage, and reservoir storage should be used to manage unscheduled flow mismatches in the conveyance system.

- The main canal system (including main branches) should have a supervisory control system and enough regulatory storage for good flow management. In canal segments downstream from regulatory reservoirs, a controlled-volume method of operation should be used to improve the system's response and recovery characteristics beyond those of conventional canal systems. Regulatory storage alternatives should be evaluated in conjunction with canal design to supplement and reduce the cost of main canal facilities.

- Flow measurement should be provided at all significant inflow and outflow locations. Flow measurement devices should be located at the headworks, at other inflow points, at bifurcations, and at turnouts. Flow measurement structures must be incorporated into conveyance system design to ensure adequate head is available.

REFERENCES

Aisenbrey, A.J., et al, 1984. *Design of Small Canal Structures*, Bureau of Reclamation, Denver Colorado.

Clemmens, A.J., 1986. "Canal Capacities for Demand Under Surface Irrigation," *Journal of Irrigation and Drainage Engineering*, ASCE, Vol.112, No.4, pp.331-347.

Clemmens, A.J., 1987. "Delivery System Schedules and Required Capacities," *Planning Operation, Rehabilitation and Automation of Irrigation Water Delivery Systems*, D.D. Zimbelman, ed., ASCE, Portland, Oregon, pp.18-34.

Merriam, J.L., 1991. "Flexible Supply Schedule Missing Link for Effective Surface Irrigation and Automation," *Irrigation and Drainage*, W.F.Ritter, ed., ASCE, Honolulu, Hawaii, pp.764-772.

Savage, M.T. and E.L. Johns, 1987. "U.S. Bureau of Reclamation: How Irrigation Projects Are Sized," *Irrigation Systems for the 21st Century*, L.G. James and M.J. English, ed., ASCE, Portland, Oregon, pp.201-208.