VERIFICATION-BASED PLANNING FOR MODERNIZING IRRIGATION SYSTEMS

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ABSTRACT

Verification-based planning is a tool to improve the irrigation system modernization planning process and to effectively monitor the post-project effects on system performance. Modernization of irrigation systems results in water *flow path changes* within the system. The planning process for modernization of an irrigation system requires careful documentation and analysis of the pre-project *(without-project)* condition and *quantified prediction* of the effects of the planned improvement *(with-project)*. Procedures and strategies for predicting, monitoring and quantifying *Targeted Flow Path Changes* caused by an irrigation system modernization project for both *without- and with-project* conditions are presented.

INTRODUCTION

Background

Rehabilitation of irrigation systems is done to bring the systems back to their initial performance capabilities. Rehabilitation may be necessary because of poor maintenance and is undertaken to take care of a backlog of deferred maintenance. On the other hand, modernization implies upgrading a system to improve its performance beyond its original potential. The purpose of this paper is to present concepts for using verification-based planning in the modernization planning process and for post-project monitoring of its effects on irrigation system performance.

Verification-based planning involves additional time and expense compared to traditional planning, due to the additional effort and data needed to achieve an in-depth understanding of the irrigation system. However, verification improves the likelihood that modernization program objectives will actually be accomplished. This is critical where public money is being spent and is of special importance for programs where the rights or interests of other water users may be compromised.

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The same methods that are presented herein for verification-based planning can also be used to verify the conservation savings that result from project implementation. Additionally, verification-based planning provides the necessary details, coupled with project cost estimates, to permit a close economic evaluation of each component of a modernization program. This provides managers and other decision makers with the information needed to evaluate alternatives for each program component before deciding whether to proceed with its implementation. Thus verification provides the quality control that assures planning objectives will be met in a cost-effective manner.

Objectives of Modernization & Flow Path Changes

Typical *local (or internal)* objectives for irrigation system modernization programs include combinations of the following:

- reduced delivery and on-farm system operational losses
- reduced operation and maintenance costs
- improved reliability in the delivery of water to farmers
- increased flexibility to provide farmers more control over their water supply
- decreased water usage per unit of land area
- increased crop production.

Typical *regional (or external)* objectives for publicly supported modernization programs are to:

- conserve water so it can be utilized for other uses and by other users
- facilitate adoption of new, desirable on-farm irrigation technologies and practices that increase water use efficiency both physically and economically
- re-manage irrigation flows to mitigate environmental, water quality and water supply conflicts

Most of the local objectives and all of the publicly supported ones involve *flow path changes* of one sort or another that are often broadly referred to as conservation practices. Reduced canal seepage and evaporation losses, and reduced delivery system operational spillage are examples of these. The focus of this paper is the use of verification-based planning for modernizing projects. This involves the implementation of new practices or measures that result in changes in one or more of the three general flow path categories. These are: *evaporative depletion flow paths*, such as evaporation from free water surfaces and evapotranspiration by crops or phreatophytes; *surface flow paths*, such as canal operational spillage and farm runoff/tailwater; and *subsurface flow paths*, such as canal seepage and deep percolation.

<u>Conceptual Overview</u>

Verification is commonly thought of as an assessment conducted *after* improvements are made to see how well modernization objectives were met. However, when included in the planning process, verification involves careful analysis of the pre-project conditions and *quantified predictions* of the effects of the planned improvements. Thus the anticipated effects can be estimated with reasonable certainty in advance of project implementation. Typically, initial predictions are made with available data and may be improved through collection of additional data, which is needed to validate assumptions and improve understanding of the irrigation system. The goal is to increase confidence in the quantification of the predictions. The desired level of confidence depends on the risks posed by uncertainty and who is taking those risks.

Once modernization objectives that involve re-managing flows are clearly identified, it is necessary to identify the flow paths into, within and leaving the system that must be changed and the degree of change necessary to achieve the desired outcomes. We call these the *Targeted Flow Path Changes*. Then it is necessary to identify the specific system characteristics that must be manipulated to achieve the *Targeted Flow Path Changes* for each of the projects that make up the modernization program. Here it is necessary to take a mechanistic view of the system, recognizing that both physical and behavioral mechanisms may need attention.

A verification-based planning strategy is a combination of an approach and a procedure for carrying out the approach for each *Targeted Flow Path Change*. There are several basic strategies for estimating the *Targeted Flow Path Changes* associated with the various components or projects of a modernization program. Selecting the most appropriate strategy for any given component or project can be a tedious and time consuming exercise. This is because each strategy has its drawbacks and each component and verification strategy combination has specific data and quality requirements.

In the text that follows we will use the word "verification" to imply both quantifying and monitoring *Targeted Flow Path Changes*.

PREDICTING AND MONITORING TARGETED FLOW PATH CHANGES

<u>Water Balances and Flow Paths</u>

The use of water balances and their associated flow paths are essential for the verification-based planning process. Figure 1 is a schematic of a comprehensive water balance that was developed for the Mid-Pacific Region of the US Bureau of Reclamation. It shows both the internal and external flow paths for a typical
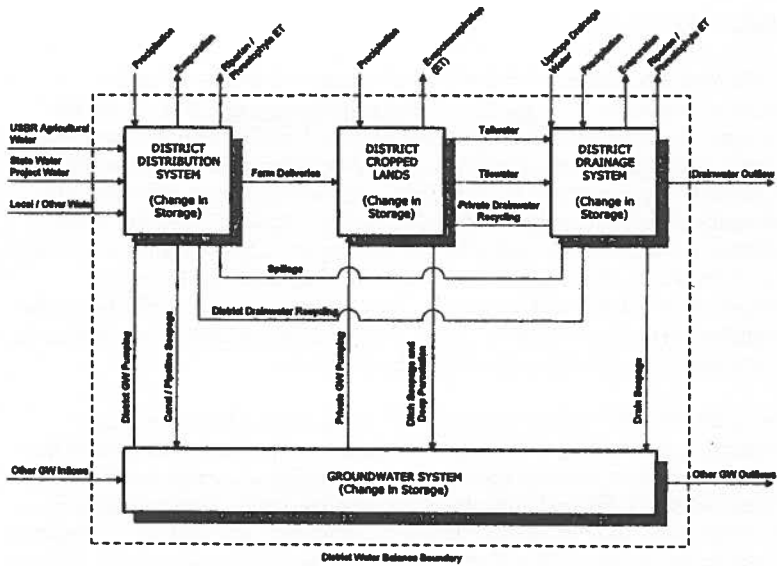
Fig.1. Global Water Balance with External Inflow and Outflow Paths and
Internal Sub-system Water Balances with the Related Internal
Flow Paths for a Typical Irrigation District

irrigation district. The sum of all the external flows into and out of the district (the
flow paths that cross the dotted line surrounding the internal water balances) plus
the change in the amount of water stored within the district's boundary must be in
balance. The same holds true for the four sub-water balances depicted within the
district.

Over yearly time periods there is usually little change in storage in the district
distribution system, cropped lands and drainage system, but there is often a
considerable change in storage within the groundwater system. However, over
short time periods the change in storage in all of the subsystems may be
considerable and must be taken into consideration in the verification analysis.

Verification requires estimating, measuring, and/or synthesizing volumes of flow
related to the various flow paths that the modernization program's individual
projects are designed to target. As will be discussed later, the first step is to
identify and quantify the *Targeted Flow Path Changes* that are required to meet
the desired outcomes. This requires a combination of measured or estimated flow
volumes that represent post-project conditions.

General Verification Perspective

Irrigation water use, and thus the quantity of water associated with the various flow paths, is affected by modernization measures and many additional factors such as cropping patterns, weather conditions and water management practices. In most cases, it is not appropriate to base the quantification of modernization effects on a direct comparison between pre- and post-project water use measurements because the additional (or non-modernization) factors will vary with time. Instead, the measurements need to be normalized to account for changes in non-modernization factors that have taken place between the pre- and post-project periods.

The general verification perspective involves a comparison between the *with- and without-project* depictions in which all non-project conditions are identical so that differences between the two represent the effects of the project. This is different than a comparison between *pre- and post-project* scenarios, which involves a span of time and thus requires making adjustments to account for any changes that are not related to the modernization project. For example, consider a tailwater recovery system installed on a 160-acre field where before the system was installed, the field discharged 80 acre-feet of tailwater per year and afterward it discharged only 20 acre-feet per year. Without consideration of changes in other factors, it would appear that the addition of the system has resulted in 60 acre-feet of conservation. However, further investigation reveals that the crop was changed between the *pre- and post-project* period from a crop for which there is little tailwater (for example, wheat) to one for which, without the system, there would be much more tailwater (for example, sugar beets). In this case, the simple pre- and post-project comparison would result in an under-estimation of conservation savings, unless the pre-project record of tailwater is adjusted to account for the crop change.

Verification-based planning requires estimating the anticipated *Targeted Flow Path Changes* and then monitoring them to provide insight and guidance as a modernization program progresses. For each flow path that will be affected (typically a delivery, spillage, return flow, or storage flow path), it is necessary to first estimate a *without-project* volume and subtract the appropriate estimated *with-project* volume from it, such that:

$$VC = V_{without} - V_{with} = VN - V \qquad \text{(Equation 1)}$$

in which,

- VC is the estimated *Targeted Flow Path Change*, acre-feet;
- $V_{without}$ or VN is an estimate of the flow path's volume of water *without the project*, acre-feet; and

- V_{with} or V is an estimate of the volume of water that would follow the flow path *with the project* in place, acre-feet.

It is not possible to measure both the *with- and without-project* conditions at the same point in time. Consequently one of the data sets must be synthesized. Figure 2 shows the typical phases that occur chronologically along the Project Timeline (from Project Conceptualization & Planning to Full Utilization) and the *with- and without-project* data sets relative to these phases. Data Sets 1 and 4 are representative of conditions prior to the implementation of each of the projects that make up a modernization program. Data Sets 1E and 1M represent estimated and measured *without-project* data. Data Sets 4E and 4S represent estimated and synthesized *with-project* data.
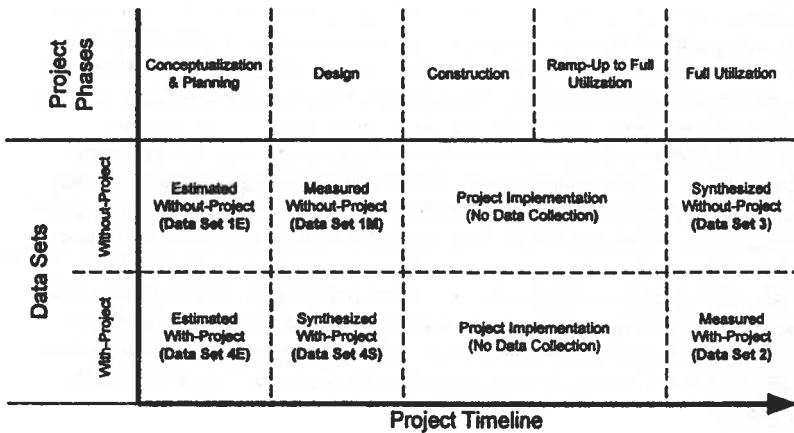
Project Phases	Conceptualization & Planning	Design	Construction	Ramp-Up to Full Utilization	Full Utilization
Data Sets — Without-Project	Estimated Without-Project (Data Set 1E)	Measured Without-Project (Data Set 1M)	Project Implementation (No Data Collection)		Synthesized Without-Project (Data Set 3)
Data Sets — With-Project	Estimated With-Project (Data Set 4E)	Synthesized With-Project (Data Set 4S)	Project Implementation (No Data Collection)		Measured With-Project (Data Set 2)

Project Timeline

Fig.2. Modernization Program Phases and Related *With- and Without-Project* Data Sets

Predicting Targeted Flow Path Changes

During the Project Conceptualization & Planning Phase there are often no or only crude flow path measurements available and it is necessary to base both the *with- and without-project data* sets (Data Sets 1E and 4E, respectively) on estimated values (see Figure 2). Projects that appear feasible based on these estimated values are normally carried forward to the Design Phase; and for verification planning purposes, field measurements should be made of actual *without-project* system performance to develop Data Set 1M. Data Set 4S representing *with-project* conditions must be *synthesized* for design purposes by employing the

information gathered in generating Data Set 1M, along with necessary assumptions, operations studies, simulations and other techniques that are commonly used during the design process. This can be a major challenge, especially for new types of projects designed to target losses requiring flow path changes that have not been addressed in the same manner before, such as lateral interceptor systems and automation of conveyance and distribution system operations.

To quantify the estimated *Targeted Flow Path Change* during the Design Phase, Equation 1 is changed to indicate the data sets (see Figure 2) needed to estimate the anticipated *without- and with-project* conditions:

$$VC = VN_{f(Set\ 1M)} - V_{f(Set\ 4S)}$$ (Equation 2)

in which:

- $VN_{f(Set\ 1M)}$ and $V_{f(Set\ 4S)}$ are measurements of *without-* and estimates of *with-project* delivery or spill volumes respectively for the pre-project time period and associated environmental conditions, acre-feet.

The practical level of rigor to apply when collecting design data and developing Data Sets 1M and 4S depends on several factors, including the cost of the project, the factors involved in predicting *with-project* conditions (projects involving operator and grower behavior are much harder to predict than those that do not depend on behavior), the risk posed by inaccurate predictions, and who is assuming the risk.

It is important to carefully plan the design data collection processes so there is a high level of confidence in Data Sets 1M and 4S, especially when dealing with projects for which the *without-project* conditions can never be replicated once project construction begins. For example, consider a main canal regulating reservoir that is being designed to eliminate a main canal spillage flow path at a particular site. If the *without-project* spillage is not adequately measured prior to constructing the reservoir, it may never be possible to completely restore the *without-project* conditions. When measuring temporally variable flow paths such as spillage, it is important to assure that diurnal, weekly and seasonal patterns are adequately characterized. As a minimum, such flow paths should be measured for at least one complete season and measurements spanning several seasons are preferable.

Monitoring Targeted Flow Path Changes

The need and approach for post-project monitoring of modernization projects depends on: a) the sensitivity of the *Targeted Flow Path Change* to environmental changes that occur over time; and b) how well the relationship between the

actions or measures employed and the *Targeted Flow Path Change* is understood. For measures whose effects are well understood and are not sensitive to environmental changes, such as canal lining, monitoring is not necessary and the pre-project predictions developed using Equation 2 hold for the post-project period.

However, where the above two criteria do not hold, Data Set 3 is needed to verify that the estimated *Targeted Flow Path Changes* have in fact occurred (see Figure 2). This is typically the case for actions or measures targeted at flow paths that are sensitive to environmental change or are affected by human behavior, such as reducing or capturing spillage. To quantify the estimated *Targeted Flow Path Change* during the Full Utilization Phase, Equation 1 is changed to indicate the data sets (see Figure 2) needed to estimate the anticipated *without-* and *with-project* conditions:

$$VC = VN_{f(set\ 3)} - V_{f(Set\ 2)} \qquad \text{(Equation 3)}$$

in which:

- $VN_{f(Set\ 3)}$ and $V_{f(Set\ 2)}$ are estimates of *without-* and measured *with-project* delivery or loss volumes respectively for the post-project time period and associated environmental conditions, acre-feet.

Data Set 3 can be developed by normalizing Data Set 1M or by synthesizing it from Data Set 2. In either case, this can be a major challenge. The normalizing process involves either: a) adjusting the estimated VN values based on pre-project Data Set 1M to simulate post-project time and environmental conditions, but without the project; or b) adjusting Data Set 1M to simulate Data Set 3 and then computing VN. However, sometimes it is possible to synthesize values for $VN_{f(set\ 3)}$ from a mixture of pre- and post-project Data Sets 1M and 2.

When collecting post-project Data Set 2 it is important to note that for projects affecting the system's behavioral characteristics there may be a period following project construction when the project is "ramping up" to Full Utilization. In such cases, for example, a lateral interceptor project, data collected during the start-up phase may not be representative of the project's long term potential. This is not a concern for projects that only involve physical characteristics such as canal lining.

Verification Feedback to Modernization Programs

Importantly, the predicted *Targeted Flow Path Changes* need to be accurately quantified during the Design Phase of a modernization project. However, these predictions depend on assumptions that involve speculation, especially for new and innovative projects that depend on behavioral responses by operators and irrigators. However, where a modernization program involves implementing

several similar projects, the opportunity may exist to validate and refine design assumptions based on the early operating results from the first project or projects. This is illustrated in Figure 3, where operating knowledge gained through *with-project* monitoring is fed into the Design Phase of subsequent similar projects.
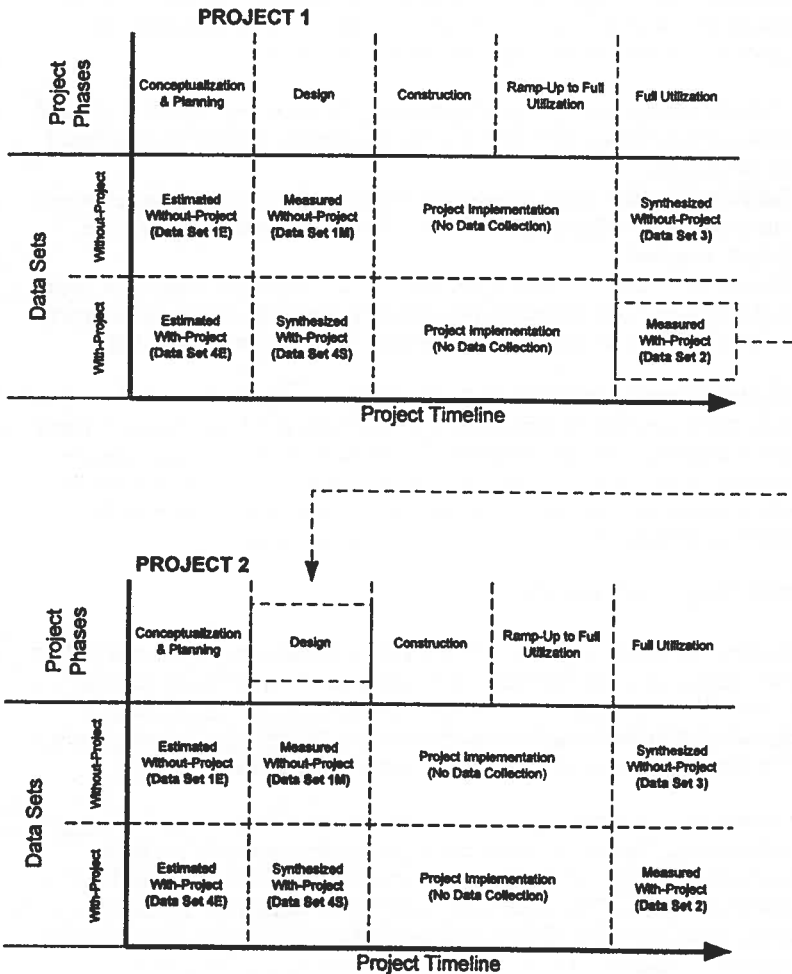

Fig. 3. Verification Feedback Into Design of Subsequent Modernization Projects

STRATEGIES FOR QUANTIFYING FLOW PATH CHANGES

Verification Approaches

As mentioned earlier each verification strategy is made up of an approach and a procedure for carrying it out. The three basic approaches for estimating the *Targeted Flow Path Change* associated with a project are:

- Delivery differential, which is the difference between representative pre- and post-project volumes of irrigation water delivered to the entire area affected by the project;
- Spill/seepage differential, which is the difference between representative pre- and post-project volumes of irrigation water that spills or seeps from the project area; and
- Return-flow fraction, which is the estimated portion of the return-flow water that results from the project and is effectively reused to reduce the amount of irrigation water required, thus representing "real" conservation savings.

Estimating the appropriate *with- and without-project* volumes to use in Equation 1 is necessary to quantify the *Targeted Flow Path Change* when using the delivery or spill/seepage differential approaches. The total return-flow volume sets the upper limit on the *Targeted Flow Path Change*. Return-flow volumes must be used in conjunction with delivery or spill differentials estimates in order to calculate the fraction of the volume that is effectively used.

Procedures for Quantifying Flow Path Changes

There are several basic procedures for estimating the necessary *with- and without-project* volumes required for each of the approaches for quantifying *Targeted Flow Path Changes*. They are differentiated by considering combinations of where and what volume estimates are needed, and the when (or time-step) to be used in converting flow rate data into the volumetric estimates.

One way to begin selecting a procedure is to first select an approach and where the subsystem or "free-body" is that encompasses the *Targeted Flow Path Changes*. (For example see the subsystem water balances in Figure 1 and the associated flow paths.) Then select the places on (or within) the free-body boundary where estimates of flow volumes are needed and when measurements are required to address the targeted changes. Following is a listing of the possibilities within these where, what, and when categories.

1) Where measurements will be made refers to both the increment of land or portion of the system that comprises the "free-body" under study and the places on (or within) its boundary where measurements are required. The

basic choices for increments of land are: a furrow, a set, a field, a farm, a lateral service area, a drainage lateral service area, the area served by multiple laterals, the area served from a main canal operating reach, or the system wide service area. The basic choices for portions of the system are: farm ditch, tailwater pond, farm drain, drainage lateral, lateral, lateral check-pond, interceptor lateral, interceptor reservoir, main drain, main canal reach, main canal check-pool, and main reservoir. The basic choices of the places on (or within) the boundary of the free-bodies where estimates of flow volumes may be required are: at farm turnouts, along farm ditches, at tailwater ponds, along field drains, along drainage laterals, at lateral headings, along laterals, at lateral check-gates, at lateral spill points, along interceptor laterals, at interceptor reservoirs; at main canal headings, along main canals, at main canal control- and check-structures, at main canal spill points, and at main reservoirs.

2) What will be measured is in effect established by the verification approach selected. It refers to the paths or components of flow that are expected to change because of the project. The basic choices are: the inflow or delivery; the outflows, which are ordered deliveries to downstream uses, spill, seepage, and evaporation; return flow; and storage changes (see Figure 1).

3) When refers to the time-step that will be used to estimate the volumes and associated differential volumes from the flow rates being measured or estimated. The basic choices are a crop season cycle, and single or multiple farm delivery cycles, 24-hour or week-long system operating cycles, and calendar cycles (such as a week or a month). A single farm delivery cycle is a multiple of 12-hour or 24-hour deliveries, and a crop season cycle is made up of the number of farm delivery cycles required for the particular crop season.

The procedures for carrying out the basic verification approaches are differentiated by the where/what volume estimates employed and the associated time-steps used. They are further differentiated by the process used in determining accumulated volume of savings. The following terms are used to differentiate between these differences:

- *Individual-event* is used when individual volume differential estimates are made for single point where/what flow rate values and single cycle time-steps (i.e., single events in both space and time) and then added to obtain the accumulated volume of savings;
- *Sequential-event* is used when individual volume differential estimates are made for single point where/what flow rate values and multiple-cycle time-steps (i.e., single events in space and multiple events in time) and then added to obtain the accumulated volume of savings; or

- *Multi-event* is used when the differential volume estimates are based on accumulated where/what values or multiple cycle time-steps (i.e., multiple events in either time or space or both).

SUMMARY

Objectives of irrigation system modernization are varied and generally involve making changes to flow paths in one or more of three general categories - *evaporative depletion flow paths, surface flow paths* and *subsurface flow paths*. Verification-based planning involves careful analysis of the pre-project *(without-project)* conditions and *quantified predictions* of the effects of the planned improvement *(with-project)*. Care must be exercised that any changes not related to the modernization project are removed or excluded from the *without- and with-project* analysis. It is not appropriate to make a direct comparison between pre- and post-project water use without normalizing conditions to account for changes in non-modernization factors.

Targeted Flow Path Changes resulting from the modernization project must be identified and quantified. During the Design Phase of the project, *without-project* flow path measurements can be made. It is necessary to synthesize the *with-project* flow path quantities for the related flow path changes. The data collection process must be carefully planned to ensure that there is confidence in both data sets and that the *with-project* data set when collected can demonstrate that the *Targeted Flow Path Changes* have in fact occurred.

Three basic verification approaches for estimating volumes of irrigation water in *Targeted Flow Path Changes* associated with a project are delivery differential, spill/seepage differential and return-flow fraction. The procedures for estimating *without- and with-project* volumes required for these approaches must consider where measurements will be made, what will be measured and the time-step as to when measurements will be made.

Verification-based planning, while requiring additional time and expense to conduct more detailed predictive analysis of conditions and to gather data, will more accurately predict water conservation results of the completed modernization project. This also provides more accurate feedback to validate and refine design assumptions for other similar projects. Coupled with cost estimates, verification details permit more accurate economic evaluation of a modernization project. This is important, even critical, for managers and other decision makers in evaluating alternatives for a program and its individual components prior to committing to proceeding with implementation. It provides a quality control component that can assure planning objectives are attained in a cost effective manner.

An actual application of verification-based planning, conducted during the implementation of the 1988 IID/MWD Water Conservation Program, titled *Lateral Canal Lining Project Case Study* is presented in the conference poster session. This case study illustrates how, through the application of verification-based planning, more accurate estimates permitted the selection and implementation of more cost-effective canals to be lined. This resulted in reducing initial concrete lining projects exceeding $250 per acre-foot to a final project cost of $131 per acre-foot.