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IRRIGATION WATER BALANCE FUNDAMENTALS

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ABSTRACT

Water balances are essential for making wise decisions regarding water conservation and water management. The paper defines the essential ingredients of water balances, and distinguishes between farm and district-level balances. An example of a hypothetical district-level balance is provided. The importance of listing confidence intervals is highlighted. Classic errors in water balance determination are noted.

CONCEPT OF A WATER BALANCE

A "water balance" is an accounting of all water volumes that enter and leave a 3-dimensioned space (Fig. 1) over a specified period of time. Changes in internal water storage must also be considered. Both the spatial and temporal boundaries of a water balance must be clearly defined in order to compute and to discuss a water balance. A complete water balance is not limited to only irrigation water or rainwater or groundwater, etc., but includes *all* water that enters and leaves the spatial boundaries.

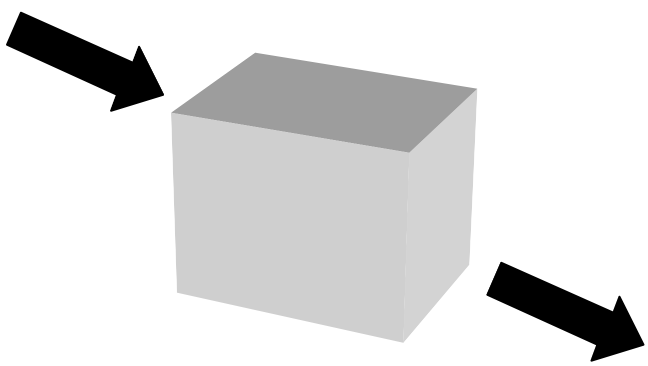

Fig 1. A Water Balance Requires the Definition of 3-D and Temporal Boundaries, and All Inflows and Outflows Across Those Boundaries As Well As the Change in Storage Within Those Boundaries.

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IMPORTANCE OF WATER BALANCES

All discussions of "scarcity of water", water rights, water conservation, and water transfers implicitly (even if not explicitly) make assumptions about water balances. The mere mention of "water conservation" implies that within the boundaries of interest, water is available to be conserved. Proper water balance computations can help avoid past errors, such as cases for which the impact of canal seepage on groundwater recharge was ignored. Likewise, there are numerous instances of projects in which spill was reduced in order to increase project water consumption, only to find out that the spill water was the source of water for downstream users - a classic case of focusing on spatial boundaries which were too small.

Western U.S. water rights typically require that irrigation water be put to "reasonable and beneficial" use, with the exact definition of "reasonable and beneficial" varying somewhat between states. A legal challenge to water rights requires an accounting of where the irrigation water goes, and how it is used. Having a good water balance is a fundamental requirement for resolving such legal issues, as the very nature of a water balance is an accounting of where all the water comes from and where it goes.

In many areas of the world there is an increased interest in water transfers from agriculture to urban or environmental uses. It is essential that proper water balances be conducted before such transfers are finalized. It is not uncommon to have a deficit agricultural water supply, yet the casual observer or misinformed policy maker may assume that there is plenty of water available for transfer.

Perhaps one of the greatest challenges for irrigated agriculture is the fact that many irrigation projects have a deficit of irrigation water, while simultaneously having other amounts of irrigation water going to unreasonable or non-beneficial uses. As a simple example, perhaps a poor water delivery system has spill, yet many project fields are under-irrigated due to poor irrigation scheduling or due to poor water delivery control (resulting in inequity and unreliable deliveries). Or it may be even more serious, with farmers in the project overdrafting groundwater through private well pumping. It may be correct to say that the spill can be captured and put to better usage. But a proper water balance will also show that the spill should not be transferred from the project, but should instead be captured and used within the project boundaries to replenish the aquifer and/or to eliminate deficit field irrigation.

Does every business have some type of accounting procedure? Yes, even if it is just in the proprietor's head. We know that excellent accounting procedures are a requirement -- not an option -- for good business. Businesses with poor accounting procedures tend to make foolish mistakes. Likewise, many irrigation districts and projects already have "water balances", but those water balances are crude and were often insufficient for the simple conditions of even decades ago.

There is no longer enough water in the right places to simultaneously satisfy all the agricultural, urban, industrial, and environmental needs. NIKE® has forever changed the life for the local hardworking shoemaker. The local shoemaker must make drastic changes or go bankrupt due to the external pressures. Likewise, the competition for water has suddenly descended on agriculture with serious consequences. With water, we need a good accounting of water supplies, of changes in storage, and of water destinations to make intelligent decisions regarding proper management of the resource. There is no choice in the matter.

SPATIAL BOUNDARIES

Water balances can be conducted for a field, for a farm, for a water district, for a hydrologic basin, etc. The same concepts apply to all units, but one must be absolutely clear about which boundary one is talking and making computations about. Table 1 shows typical spatial boundaries of various areas. The lower boundary for irrigation (water) districts can be quite different, depending upon whether there is or is not groundwater pumping or a high water table.

Table 1. Spatial Boundaries of Various Areas.

Space	Upper Boundary	Lower Boundary	Horizontal Boundaries
Farm	Crop canopy	Bottom of root zone	Farm fields
Conveyance system	Water surface	Canal bottom	All diversions, spills, and discharge points
Water District without groundwater pumping	Crop canopy	Bottom of root zone	District
Water District with groundwater pumping	Crop canopy	Bottom of aquifer	District
Water District without groundwater pumping, but with a high water table	Crop canopy	Bottom of aquifer that is tied into the high water table	District

On-farm irrigation efficiencies and on-farm water management may or may not impact water district efficiencies. There is frequently confusion about this topic. A classic case can be illustrated as follows:

Assume

- Three units of irrigation water arrive within a district
- The district has 3 farms
- There is no water supply or source for the district other than the surface irrigation water
- All 3 units are delivered to the first farm
- The consumption of water on first farm is 1 unit

- Somehow, all the other 2 units of water are recaptured and are delivered to the second farm. The consumption of the second farm is 1 unit.
- Somehow, the unconsumed unit is recaptured and is delivered to the third farm. The consumption of the third farm is 1 unit.

How much water was consumed in the district?

Obviously, the answer is 3 units.

The incorrect answer would have been to treat the farm supplies (3 + 2 + 1 = 6 units) as district supplies, because the question deals with the district boundaries, through which only 3 units of water passed. The internal recirculation is interesting, and may be very important because of decreased water quality, poor yields, and excess pumping -- but that doesn't mean it should be counted in a district water balance. Unfortunately, some water conservation programs for districts are based upon projected savings from recovering the individual spills (3 units in the case above). Good water, power, and fertilizer management would result in less water spill from individual fields, but that would only decrease the gross (not net) water requirement for each individual field - not for the district as a whole.

Good water management may actually increase water consumption through increased evapotranspiration (ET). If irrigation management can be improved to reduce unwanted plant stress, then by definition, the ET is increased. Typically, this increase in ET is simultaneously accompanied with an increase in yield, so the water use efficiency (defined here as yield per unit of water consumption) would improve. But for the overall basin, this good water management might actually increase water consumption - resulting in the opposite of water conservation. A good water balance will indicate whether this is a possibility.

TEMPORAL BOUNDARIES

A water balance has temporal (time) boundaries as well as physical boundaries. All of the values of water balances (rain, irrigation water supply, ET, etc.) change from one year to another. It is unwise to examine the balance for just a single year -- it may be a wet year or a drought year, or perhaps even a "normal" year. Some types of data (groundwater inflows, outflows, and change in storage, crop ET) are difficult to evaluate accurately on a single year basis. Therefore, a multi-year evaluation of the data is recommended for the calculations of the water balance components. Data for single years should be determined in most cases, but should be combined into one larger table for a 3 or 4 year "average" computation.

Likewise, good estimates of on-farm irrigation efficiency typically require a careful soil-water balance be conducted on a daily or weekly basis. Using gross annual amounts can give huge errors, because of issues associated with proper timing of irrigations, non-uniformity of irrigations, and the frequency of rainfall events. Furthermore, the root zone moisture content at the beginning and the end of the year may be very different, depending upon the type of crops grown in sequential years. In summary, good on-farm efficiency estimates require water delivery (and rainfall) measurements throughout the year, for multiple years, and a good understanding of crop water requirements, evaporation, and irrigation system distribution uniformities.

For more information on boundaries and water balances, refer to Burt et al. (1997). That ASCE reports deals more specifically with irrigation efficiency and irrigation sagacity - both of which require irrigation water balances.

INTERNAL BALANCES AND PARTITIONING THE WATER COMPONENTS

A "water balance" is not the same as an "irrigation water balance". An "irrigation water balance" is typically more difficult to construct than a "water balance" because the specific *portion* of ET and Leaching Requirement (LR) that originated as irrigation water (as opposed to rain water or some other source water) must be estimated. All other components of water which leave the boundaries (spill, deep percolation, etc.) must also be broken out as (i) a certain percentage irrigation water and (ii) as a certain percentage from the other sources. It is problematic to do this separation.

There are other sub-categories of water balances. These include rainwater balances, on-farm irrigation water balances, conveyance water balances, root zone moisture water balances, and groundwater balances.

Reasons to develop these sub-categories of water balances include:

1. The emphasis of a study may be narrow. For example, conveyance water balances, which only look at canal inflows and outflows such as seepage, deliveries, and spills, can be valuable in determining <u>how</u> to modernize a delivery system. In such a case, it is unnecessary to have a complete water balance of the district, and the temporal boundaries can be fairly limited as well.
2. Sub-categories of water balances may not shed light on district-level water balance *quantities* in some cases, but on-farm water balances and conveyance water balances shed light on what internal district *processes* must be modified to change the district-level water balance. For example, if a district loses a large percentage of water as surface outflows, it is important to know if this is tailwater from fields, spill from canals, or uncontrolled inflows to the district from neighboring areas.

3. Sub-categories of water balances may be needed to solve for key values in the district-level water balance. Seepage from canals (which is <u>un</u>important for the water balance in districts with conjunctive use) may be determined as a closure term in a conveyance water balance (discussed in a later section of this paper).

An even more complex partitioning involves classification of the irrigation water destinations as "beneficial" and "non-beneficial", and "reasonable non-beneficial" and "unreasonable non-beneficial". Such partitioning is required if one desires to compute values of irrigation efficiency or irrigation sagacity (Burt et. al., 1997). The process of determining irrigation efficiency and sagacity is:

1. Define the spatial and temporal boundaries.
2. Complete an *overall* water balance with all components of water.
3. Develop an *irrigation* water balance.
4. Partition the irrigation water destinations as "beneficial, non-beneficial, reasonable non-beneficial, or unreasonable non-beneficial".

CONFIDENCE INTERVALS.

Once the water balance components have been identified and quantified, an estimate of the confidence interval (CI) for each value should be made. A confidence interval of "6.0" indicates that one is 95% certain that the correct value lies between plus or minus 6% of the stated value. The purpose of using confidence intervals (CI) on figures and tables is to reinforce the fact that we rarely know many values with precision - even though discussions of those values often seem to assume that we do know them as absolute values. In fact, we are not even "95% certain" of the CI values.

The CI of some values will depend upon the CI of the other measurements. A description of how to mathematically combine the component CI values into the CI of the final computation can be found in Clemmens and Burt (1997).

A curious phenomenon seems to occur rather frequently in the U.S. and abroad. Engineers have decided to ignore some essential components of water balances because they do not have good estimates of their values. Needless to say, all components must be included in a water balance -- not just those components that have a small confidence interval.

CLOSURE TERMS

Water balances typically have "closure terms". That is, some component values cannot be directly measured with reasonable accuracy. Such a value may be estimated as the difference between two or more better-known values. As mentioned earlier, sub-categories of water balances are often developed as a means of providing a reasonable value for a closure term.

Typical examples of components with values that are estimated as closure terms are listed below:

1. Canal seepage. It is very difficult to directly measure seepage on extensive canal systems. Direct measurements can be made with ponding tests, but these can be expensive and have a limited sample size. Seepage is estimated for studies as a closure term by:

   $$\text{Seepage} = \text{Diverted} - \text{Canal Evaporation} - \text{Deliveries} - \text{Canal Spills} \qquad (1)$$

   It is common to see reported seepage values fluctuating wildly from day to day, even with negative values being reported occasionally. Such values are obviously solved as closure terms, and have been developed with poor measurements of the other 4 values in the equation.

2. Evapotranspiration (ET). An accompanying paper by Bert Clemmens expands on the topic of ET computation. Typically, ET estimates are made from computations that utilize weather data (to compute a reference ET), crop acreage reports, knowledge of irrigation timings as well as planting dates and harvest dates, and crop coefficients. Such estimates, even if made with seemingly exquisite care, may only be within 15-20% of truth in the real world of district water balances.

   Occasionally the hydrology of an area allows ET to be computed more accurately as a closure term. The Imperial Valley has such a hydrology. There is no significant groundwater movement or change in storage, and surface inflows and surface outflows are measured quite well. Furthermore, there is almost no rain. Simplistically,

   $$\text{ET} = \text{Surface inflows} - \text{Surface outflows} \qquad (2)$$

   Conversely, the Coachella Valley -- with the same water supply, climate, and water quality -- has a different hydrology that allows groundwater pumping and subsurface lateral movement across the district boundaries. In the case of Coachella Valley, ET cannot be most accurately computed with the same methodology as in Imperial Valley.

4. On-farm deep percolation. It is almost impossible to directly measure the quantity of on-farm deep percolation on individual fields. Even if a field is in a high water table situation and has tile lines, the tile line discharges are affected by upward fluxes of water as well as lateral inflow/outflows from neighboring fields -- which means the tile drain discharge may be greater or less than the actual field deep percolation. Sometimes deep percolation is

estimated with assumed "leaching fractions" based on soil salinities as compared to the water salinities, but this can be a very fragile computation since the leaching efficiencies vary tremendously between soil types.

Often the deep percolation for a field without a high water table is estimated as a closure term as follows:

$$
\begin{aligned}
\text{Deep percolation} = \; & \text{Irrigation water inflow} \\
+ \; & \text{Rainwater} \\
- \; & \text{Evaporation} \\
- \; & \text{Crop ET} \\
- \; & \Delta\text{Root zone storage} \\
- \; & \text{Tailwater runoff}
\end{aligned} \qquad (3)
$$

Because the uncertainty of each value in equation (3) can be great, deep percolation for fields without a high water table is often better estimated on an event-by-event basis. This requires knowledge of the soil moisture depletion (SMD) prior to irrigation, the volume of irrigation water applied to a known area during an irrigation, the tailwater runoff, and the Distribution Uniformity (DU) of each irrigation.

ON-FARM VS. IRRIGATION DISTRICT/PROJECT

The obvious has already been stated: the spatial boundaries of a field or farm are different from the boundaries of an irrigation (water) district. But people frequently want to use on-farm irrigation efficiency measurements to estimate district-level irrigation efficiencies. Ken Solomon addresses some aspects of this topic in another paper of this conference.

Two simplified comparisons are made here between on-farm and district-level irrigation efficiencies. The importance of designing a proper balance should become clear.

<u>Westlands Water District</u>. The first example is Westlands Water District in the west-central zone of the San Joaquin Valley. The three important conditions to consider for Westlands WD are as follows:

1. The water distribution system for the district is pipelined. This means that there are almost no distribution system losses such as spill or deep percolation. In any case, deep percolation may not be important, as seen below.
2. Some of the deep percolation from some fields shows up as a high water table in downslope fields. This is not desirable from the standpoint of the downslope farmers, but a large portion of the crop ET on the downslope fields is supplied by the high water table source.

3. There is no unrecovered tailwater from individual farms -- it is prohibited.

The result of these 3 conditions is this: Of the irrigation water that enters the district boundaries, there is no loss through the district conveyance system, and no surface runoff across the district boundaries. This limits the inefficiencies to non-beneficial on-farm deep percolation and evaporation of irrigation water. However, some of that non-beneficial deep percolation is inadvertently recycled within the district boundaries via high water tables. The net result for Westlands Water District is:

WWD District-level irrigation efficiency > WWD avg. on-farm irrigation efficiency

<u>Imperial Irrigation District</u>. The Imperial Irrigation District (IID) has the following important characteristics that impact the relative values of district vs. farm irrigation efficiencies:

1. The major farm-level inefficiency is uncollected tailwater runoff. This tailwater, once it leaves the farm boundaries, flows through district drains into the Salton Sea. There is no district-level recirculation of this on-farm loss.
2. There is little-to-no recirculation of on-farm deep percolation water. In most cases, this would not be a significant amount anyway, since the heavy clay soils limit the amount of deep percolation and the tile water is typically too salty to reuse. Basically, all on-farm deep percolation leaves the district boundaries.
3. There are losses in the irrigation district conveyance system which leave the district boundaries. These losses include some canal seepage, as well as some canal spills. There is also some canal evaporation loss.

The results of these 3 conditions are these: both distribution and on-farm losses which exit the district boundaries. There is almost no internal recirculation of on-farm losses. The overall result is:

IID District-level irrigation efficiency < IID avg. on-farm irrigation efficiency

In summary, for the two largest irrigation districts in California one has exactly the opposite relationship between average farm-level irrigation efficiency values and district-level irrigation efficiency values. Good water balances are essential tools for this type of analysis.

CLASSICAL WATER BALANCE ERRORS

An optimist believes that we will learn from our mistakes. This optimistic section lists some of the common errors encountered with developing and computing water balances. These include:

1. Not defining the spatial 3-D boundaries of the water balance.
2. Improperly defining the spatial 3-D boundaries of the water balance.
3. Not defining the temporal boundaries of the water balance.
4. Improperly defining the temporal boundaries of the water balance.
5. Insistence that there is only one way to compute the value of a component such as ET. It has already been pointed out that there are at least 2 different procedures to compute ET. Additional methods exist, and they depend upon the type of data available, the hydrology, type of crop, weather conditions, and even the method of on-farm irrigation.
6. Belief that water balances give results with extreme accuracy - e.g., arguing over the difference between 76.5% irrigation efficiency and 77.1% irrigation efficiency when the key values are not known within ± 10%.
7. Not identifying confidence intervals
8. Using on-farm water balances and efficiencies to represent district-level water balances and efficiencies
9. Confusing field irrigation Distribution Uniformity (DU) with field-level irrigation efficiency, or even with district-level irrigation efficiency.
10. Using measurements from a single irrigation event to predict annual values. For example, irrigation efficiencies are typically very different during the Spring as compared to the Summer months in California.
11. Using one year of data and water balance results to make long-term recommendations.
12. Double counting groundwater. This may be the rule rather than the exception with existing district-level water balances in California. The groundwater pumping occurs within the boundaries of the districts, and the source of the groundwater is often the deep percolation from the irrigated fields. It is certainly true that for most farms the groundwater pumping is considered a *farm* source, but the vertical farm-level water balance boundaries are at the bottom of the root zone. The vertical boundaries of an irrigation district are quite different if there is conjunctive use (see Table 1).
13. Adding and subtracting values that are important but which simply do not belong in a water balance.
14. Using assumed values. A classic assumption in overseas projects is value of field-level deep percolation on rice soils. What is even more curious is the common use of the field-level rice deep percolation for project-level water balances -- even though the field level deep percolation is recycled within the project. There is confusion between the necessity of rice deep percolation and how the value should be used in water balances.

EXAMPLE OVERALL WATER BALANCE

Table 2 and Fig. 2 provide an example of components, and the organization of data, which are needed for a detailed district-level water balance. Examination of Table 2 will immediately indicate that some of the required data is probably unavailable right now for most irrigation districts and projects. As mentioned earlier, the lack of data is not justification for ignoring water balance components. A preliminary water balance will show what data is available, what data is lacking, and what the relative importance of each component is.

For example, a certain value may not be known within plus or minus 100% (CI = 100). However, that particular component may have a very small impact on the overall water balance. Therefore, it may be best to concentrate on improving data collection for another water balance component that is better known, but which actually provides greater uncertainty for the overall balance value.

Table 2. Hypothetical Overall District-Level Water Balance (from Styles and Burt, 1998).

Overall Water Budget

								CONFIDENCE INTERVAL (%)	
		Surface and Subsurface Water Inflows	**1993**	**1994**	**1995**	**1996**	**Average**	PLUS (+)	MINUS (-)
+	**A1**	Surface Water Total Irrigation Deliveries	385,000	330,000	400,000	385,000	375,000	5	5
+	**A2**	Wheeled Water	50,000	70,000	65,000	80,000	66,250	10	10
+	**A3**	Subsurface Lateral Inflow	40,000	40,000	40,000	40,000	40,000	30	30
+	**A4**	Uncontrolled Surface Flows from outside of the Service Area	750	750	750	750	750	100	50
+	**A5**	Creek Inflows	25,000	500	25,000	20,000	17,625	50	25
	A6	Portion of Creek flow that recharges to Groundwater	12,500	250	12,500	12,500	9,438	50	25
+	**B1**	Gross Rainfall in the Service Area	160,000	100,000	180,000	190,000	157,500	15	15
		Surface and Subsurface Water Outflows							
		Beneficial Uses of Imported Surface Irrigation Water							
-	**C1**	Crop ETiw of Class I Lands	275,000	290,000	240,000	272,500	269,375	15	15
-	**C2**	Crop ETiw of Class II Lands	21,500	22,000	20,000	22,000	21,375	30	30
			0	0	0	0			
	C3	Volume of Water Required for LR of Class I Lands	14,000	15,000	12,500	14,000	13,875	-	-
-	**C4**	LR leaving as Surface Water (tile water)	4,500	3,000	5,000	4,500	4,250	30	30
-	**C5**	LR leaving as Groundwater	9,500	12,000	7,500	9,500	9,625	30	30
	C6	Volume of Water Required for LR of Class II Lands	1,000	1,000	1,000	1,000	1,000	-	-
-	**C7**	LR Leaving as Surface Water (tile water)						50	25
-	**C8**	LR Leaving as Groundwater	1,000	1,000	1,000	1,000	1,000	50	25
-	**C9**	Municipal and Industrial Consumptive Use	6,500	6,500	6,500	6,500	6,500	30	30
		Destinations of Non-Irrigation Water							
-	**D1**	Crop ET(non-iw)	97,500	90,000	92,500	92,500	93,125	15	15
-	**D2**	Crop ET(non-iw) of Class II Acreage	7,500	7,000	7,500	7,500	7,375	30	30
-	**D3**	Evaporation from roads, cities, canal banks, etc.	8,000	5,000	8,500	9,000	7,625	30	30
-	**D4**	Surface Water Discharge due to Rain Runoff and Creek Flows	27,500	4,000	31,500	25,000	22,000	30	30
-	**D5**	Subsurface Outflow above aquifer boundary due to Rain, Subsurface Inflow and Creek Recharge	47,500	45,000	50,000	47,500	47,500	30	30
-	**D6**	Subsurface Seepage through aquifer boundary due to Rain, Subsurface Inflow and Creek Recharge	21,000	21,000	21,000	21,000	21,000	30	30
-	**D7**	Wheeled Water (same as A2)	50,000	70,000	65,000	80,000	66,250	10	10
		Non-Beneficial but Reasonable Uses of Imported Surface Irrigation Water							
-	**E1**	Canal Evaporation	6,500	6,500	6,500	6,500	6,500	30	30
-	**E2**	Evaporation from roads, canal banks, etc.	5,000	5,000	5,000	5,000	5,000	30	30
-	**E3**	Surface Water Discharge (canal spill)	12,500	11,000	15,500	15,000	13,500	50	25
-	**E4**	Phreatophyte ET	3,500	3,500	3,500	3,500	3,500	50	25
-	**E5**	Surface Water Discharge (estimate 40% of tailwater)	19,000	17,500	22,500	21,500	20,125	30	30
		Non-Beneficial and Unreasonable Uses of Imported Surface Irrigation Water							
-	**F1**	Surface Water Discharge (estimate 60% of tailwater)	29,000	26,500	38,000	32,500	31,500	30	30
		Change in Groundwater Storage (Source or Sink of Water)							
=	**G1**	**Change in Groundwater Storage (Closure = Inflows - Outflows)**	**8,250**	**(105,250)**	**63,750**	**33,250**	0	30	30
		Water Balance Closure = (A1+A2+A3+A4+A5 +B1) -							
		(C1+C2+C4+C5+C7+C8+C9 +D1+D2+D3+D4+D5+D6+D7 +E1+E2+E3+E4 +F1)							
		Change in Groundwater Storage due to Precipitation							
	G2	* Deep Percolation due to Rain (Est. 30% of Gross Rainfall)	48,000	30,000	54,000	57,000	47,250	30	30
	G3	* Estimated Lateral Outflow due to Rain (158,000 AF - A3-C5-C8-A6)	95,000	104,750	97,000	95,000	97,938	30	30
	G4	* Balance of Rain that goes into storage G4 = (G2 - G3)	(47,000)	(74,750)	(43,000)	(38,000)	(50,688)	30	30
	G5	**Change in Irrigation Water Groundwater Storage G5 = (G1 - G4)**	55,250	(30,500)	106,750	71,250	50,688	30	30

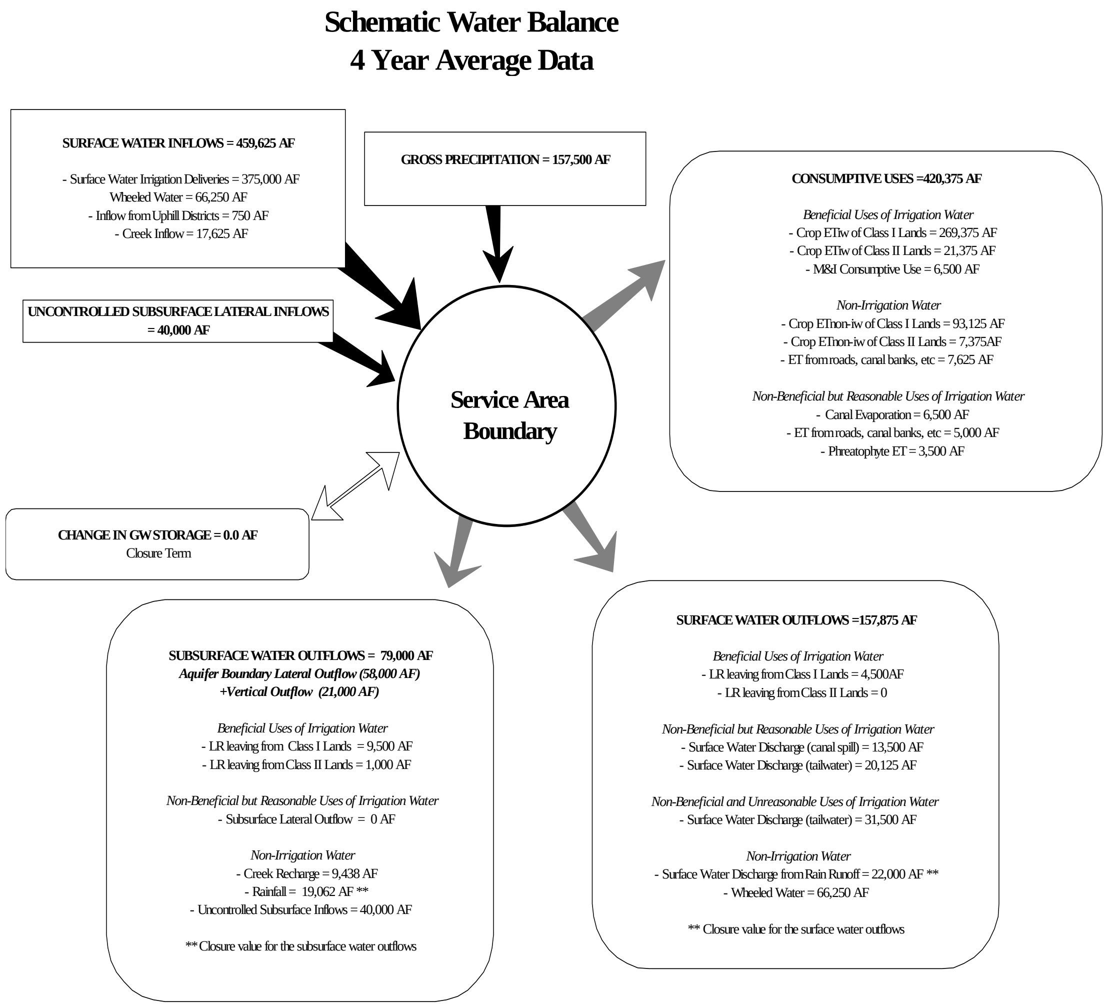

Fig. 2. Schematic of Detailed Water Balance (from Styles and Burt, 1998).

SUMMARY

The complexity of water demands requires that we understand our water sources and water destinations. It is only with a good water balance in hand that we can make good long-term decisions on overall water conservation and management plans.

Although water balances have been computed for decades, good water balances are in their infancy for irrigation projects. This is especially true for the subsurface components, where we typically have very little good quantified information about flow between irrigation districts.

This paper identifies key concepts and components of water balances, and also lists common errors that should be avoided. Water districts and planners are encouraged to begin the development of good water balances in order to identify data gaps that can be filled.

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