State of California
The Natural Resources Agency
DEPARTMENT OF WATER RESOURCES
Bay-Delta Office

On Estimating Net Delta Outflow (NDO)

Approaches to estimating NDO in the Sacramento-San Joaquin Delta

March 2016

This report introduces and defines the concepts relating to calculating Net Delta Outflow (NDO) for the Sacramento – San Joaquin Delta. It highlights the challenges, the current approaches and puts forward the best science available in estimating NDO. It concludes with future steps that could be taken in the short-term and long-term to improve the current state of the science.

Edmund G. Brown Jr.	**John Laird**	**Mark W. Cowin**
Governor	Secretary for Natural Resources	Director
State of California	The Natural Resources Agency	Department of Water Resources

This page intentionally left blank

State of California
Edmund G. Brown Jr., Governor

Natural Resources Agency
John Laird, Secretary for Resources

Department of Water Resources
Mark W. Cowin, Director

Carl A. Torgersen
Chief Deputy Director

Kasey Schimke
Asst. Director, Legislative Affairs

Gary Bardini
Deputy Director,
Integrated Water Management

John Pacheco
Deputy Director,
California Energy Resources Scheduling

Ed Wilson
Asst. Director of Public Affairs

William Croyle
Deputy Director,
Statewide Emergency
Preparedness and Security

Mark E. Andersen
Acting Deputy Director,
State Water Project

Spencer Kenner
Office of the Chief Counsel

Kathie Kishaba
Deputy Director,
Business Operations

Taryn Ravazzini
Deputy Director,
Special Initiatives

Bay-Delta Office

Paul A. Marshall.. Chief

Modeling Support Branch

Francis Chung.. Branch Chief, Modeling Support Branch

This report was prepared under the supervision of

Tara Smith .... Chief, Delta Modeling Section

By

Nicky Sandhu…………………………………………………Senior Engineer, Water Resources
Bob Suits ……………………………………………..………..Senior Engineer, Water Resources
Eli Ateljevich…………………………………………………Senior Engineer, Water Resources
Liheng Zhong…………………………………………………Environmental Scientist
Tariq Kadir…………………………..……………………...Senior Engineer, Water Resources

Contents

Contents i
1 Introduction 1
1.1 Background 1
1.2 NDO vs NDOI: Nomenclature and Conceptual Differences 2
1.2.1 Defining Net Outflow 4
1.2.2 Accuracy 6
2 Delta Consumptive Use and Channel Depletion 7
2.1 Delta Consumptive Use and Channel Depletion 7
2.2 DAYFLOW 8
2.3 Delta Island Consumptive Use Model 10
2.4 Delta Evapotranspiration of Applied Water Model 14
2.5 Groundwater as a Source of Water to Meet Delta Consumptive Use 17
2.6 Comparison of key results from DAYFLOW, DICU, and DETAW models 19
2.7 Land use Data 24
3 Direct measurement of Net Flow 31
3.1 Background 31
3.2 Multiple Control Volumes: Expanding Direct Measurement 32
4 Salinity Inversion 37
4.1 Outline of approach 37
4.2 Example using PEST and Martinez Salinity Generator 37
5 Summary, Recent Activities and Possible Future Directions 39
5.1 Summary 39
5.2 Recent Activities and Possible Future Directions 39
5.2.1 Delta Water Master led investigations 39
5.2.2 Groundwater 39
5.2.3 Improved reporting 39
5.2.4 Increased instrumentation for flow 40
6 Bibliography 41

List of Figures

Figure 1: Map showing the location of the four NDO outflow stations. 3
Figure 2: Comparison of DAYFLOW NDOI and two calculations of NDO..... 4
Figure 3: DSM2 modeled flows corresponding to three possible NDO nominal locations...... 5
Figure 4: Schematic showing the water balance for Delta Islands 8
Figure 5: Yearly Repeating Seasonal Pattern of Gross Channel Depletions Assumed in DAYFLOW..... 9
Figure 6: Example of DAYFLOW estimation of net channel depletion..... 10
Figure 7: Delta land use areas used in DICU for critical and dry years versus all other years...... 11
Figure 8: Example of leaching volume and seasonal variation assumed in DICU 12
Figure 9: Theissen Polygon and precipitation stations used in DICU to estimate Delta-wide precipitation 13
Figure 10: DETAW Model Consumptive Use Subareas 15
Figure 11: Calibration of DETAW crop coefficients to Match SEBAL Consumptive Use, 2007 16
Figure 12: Validation of DETAW crop coefficients to SEBAL, 2009 16
Figure 13: Water Supply and Disposal for Delta Lowlands Reported in DWR Report 4 (1956)...... 17
Figure 14: Estimated Contributions to Medford Island Groundwater from Assumed Sources. 18
Figure 15: Estimated Contributions to McDonald Island Groundwater from Assumed Sources..... 18
Figure 16: Estimated monthly rate of change in groundwater storage within Delta Lowlands. 19
Figure 17: Key Long-Term Monthly Average Volumes for Oct – Sep, 1990 – 2014 20
Figure 18: Key Long-Term Monthly Average Volumes for Jun – Oct, 1990 – 2014...... 21
Figure 19: Sample Comparison of Daily Delta Channel Depletion for DAYFLOW, DICU, and DETAW 22
Figure 20: Sample Comparison of Daily Delta Outflow Index for DAYFLOW, DICU, and DETAW..... 23
Figure 21: Closure in a control volume around the Rio Vista (SRV) station. 32
Figure 22: Control volumes available as of 2015. 34
Figure 23: Mass balance in a reach of Old River...... 35
Figure 24: Mass balance around Delta Cross Channel. 35
Figure 25: Mass balance above Jersey Point. 35
Figure 26: NDOI vs Estimated NDO using Martinez EC..... 38

List of Tables

Table 1. Specific crop classes in CDL and their corresponding land use category for the model of this study..... 24
Table 2. Projected changes in crop acreage from year 2014 to 2015..... 28
Table 3. Dates of updating land use data and the corresponding data sources 28
Table 4. Projected 2015 acreage of land use categories in Delta..... 29
Table 5. Projected 2015 acreage of land use categories for all Water Budget Areas (WBA) in the Sacramento Valley. Hand-picked and machine-picked tomatoes are not distinguished..... 30

1 Introduction

1.1 Background

The Sacramento-San Joaquin Delta and Suisun Marsh lie near the confluence of the Sacramento and San Joaquin Rivers, and comprise the upper part of a partially mixed tidal estuary that flows out through the Carquinez Strait into the San Francisco Bay and ocean. Salinity intrusion along the west-east axis in the estuary responds to the balance between tidal and net flow. These two forces are very different in magnitude, controllability and in how they influence the estuary. Tidal flows move upstream (flood) and downstream (ebb) and tidal flow magnitudes can be large at times (600,000 cfs at Martinez, 150,000cfs at Rio Vista). While the bulk of the flow is oscillatory and does not result in net transport, the tides do bring about upstream transport through complex circulation and dispersion mechanisms fed by asymmetries between flood and ebb. Net delta outflow, the net when tidal flow is filtered or disregarded, is usually one or two orders of magnitude smaller, but more directly moves the salinity field downstream (assuming outflow is positive).

Net Delta Outflow Index (NDOI) is the regulatory representation of net Delta outflow, defined in SWRCB Decision 1641 (D-1641). The NDOI was to be computed daily. NDOI is simply a water balance around the Delta using measured inflows of the major rivers and streams, measured exports by the major water projects and estimates of other water agencies' diversions, channel depletions and precipitation. There have been changes in these calculations over the years due to

- Additional surface water diversion locations
- Gaging stations being changed or dropped out due to lack of maintenance
- Change of location of gaging stations without accounting for consumptive use along the stream before it enters the administrative Delta

Several aspects of the methodology are out-of-date, and D-1641 references improvements to the channel depletion component that were underway as far back as 1995. In fall 2015, State Water Resources Control Board (SWRCB) requested that the DWR provide technical guidance on the best available consumptive use models and more broadly on the subject of net flow calculation.

This document represents our response. Key recommendations and comments are as follows:

* At this point in time, an NDOI-like water balance remains the best choice as an indicator of net outflow, but should be updated to incorporate improvements in consumptive use estimates and to correct a few known accounting errors such as the inflow from Yolo Bypass in summer.

* The monthly Delta Island Consumptive Use (DICU) model represents our most mature consumptive use estimate. It was the in-progress effort mentioned in D-1641 and has been ensconced in planning and modeling practice throughout the Bay-Delta community for many years. Much work has been done to replace DICU with a daily model in recent years. The Delta Evapotranspiration of Applied Water (DETAW) includes finer time scales and better soil moisture accounting. DETAW, a consumptive use model, is completed. However in order to estimate net channel depletions, which has a more direct impact on outflow, estimates for factors such as groundwater use need to be incorporated in the calculations along with DETAW amounts. As a result, this model, and its post processed net channel depletions, has not been officially released, in part because of some uncertainties over the contributions of seepage from channels and ground water uptake. Input, development and acceptance of groundwater assumptions is needed by a wider community.

* The 4-station (Rio Vista, Jersey Point, Dutch Slough, Threemile Slough) direct measurement approach to outflow is inaccurate and should not be used to calculate Net Delta Outflow or to corroborate NDOI. This recommendation is based on accuracy and the nature of the product.

* DWR and other institutions should continue to perform more measurements, field studies and investigations to refine estimates.

The bulk of this document is analysis supporting the above conclusions, though we also describe a few more novel approaches that are currently being pursued, some involving direct measurement over the full flow monitoring network and some involving inversion of salinity models.

1.2 NDO vs NDOI: Nomenclature and Conceptual Differences

The difference between Net Delta Outflow Index (NDOI) and the Net Delta Outflow (NDO) has received some attention in recent years. Any comparison of these approaches must span two subjects, one having to do with the nature of the final product and the other having to do with implementation and accuracy. The discussion here centers on indices that are most often seen in practice, but the remarks are pertinent for nearly any proposal.

NDOI is an index of outflow used for many regulatory and operational purposes. The NDOI calculation infers outflow from a Delta water flow balance including tributary flows, channel depletions and exports. For clarity, we will refer to the current implementation as NDOI and use NDOI-like when we are envisioning an enhancement based on improved consumptive use and Yolo accounting.

NDO is often used generically, but when it is described as an observation this is usually the computed sum of tidally filtered flows at Dutch Slough, Jersey Point, Rio Vista and Threemile Slough (see Figure 1).

In their present forms, NDOI and NDO often disagree markedly, as indicated in Figure 2 which compares Dayflow NDOI to NDO in 2002.

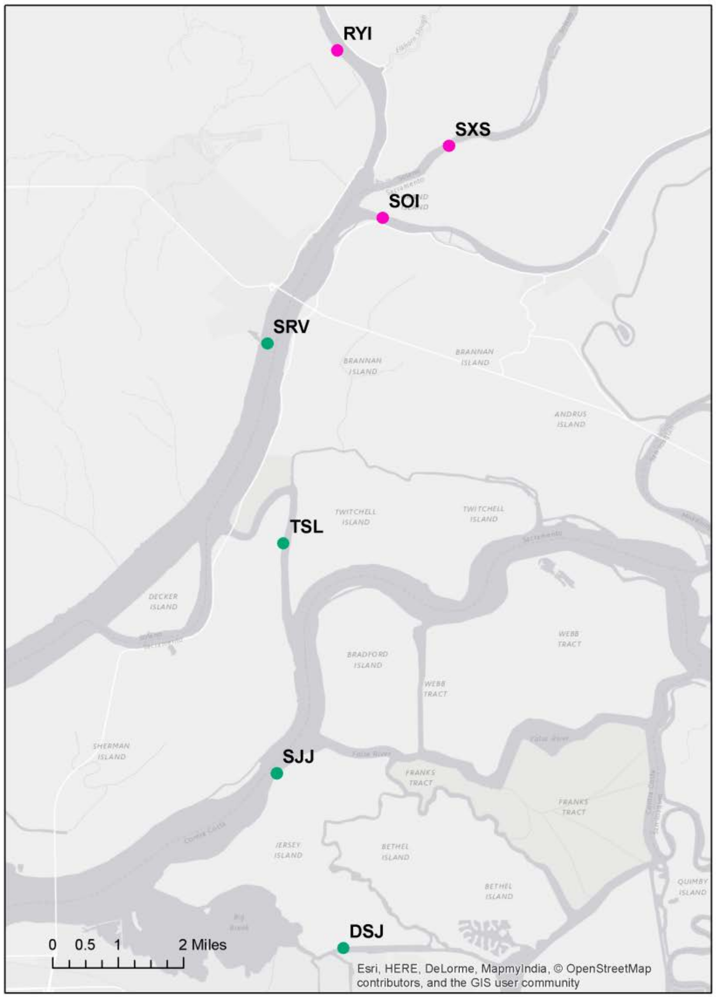


Figure 1: Map showing the location of the four NDO outflow stations at Rio Vista (SRV), Threemile Slough (TSL), San Joaquin at Jersey Point (SJJ) and Dutch Slough (DSJ) shown in green. Additional stations used to form a control volume with SRV are Cache Slough at Ryer Island (RYI), Steamboat at the Sacramento (SXS) and Sacramento below Isleton (SOI) shown in pink.

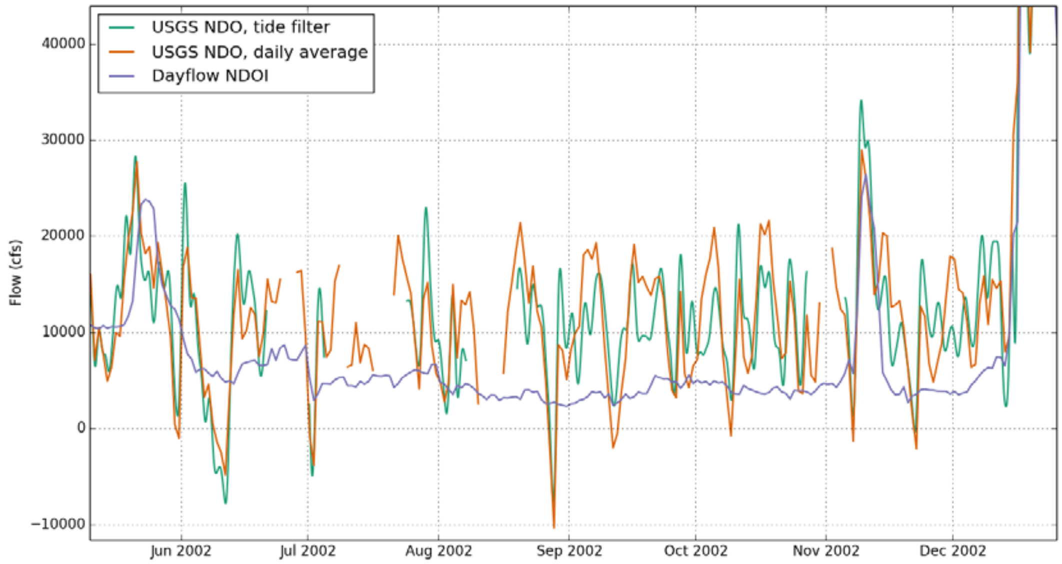


Figure 2: Comparison of DAYFLOW NDOI and two calculations of NDO, one using a cosine-Lanczos (squared) filter and the other with simple daily averaging.

1.2.1 Defining Net Outflow

Supposing both NDOI and NDO were calculated without error, the two curves in Figure 2 would be more centered vertically and the major difference between them would be that NDO contains substantial subtidal oscillations. These are a conspicuous feature in Figure 2 and the cause of this undulation is the much-discussed filling and draining of the Delta that appears in irregular cycles of 4-30 days. Filling and draining is forced by offshore low pressure events and nonlinear transport processes excited by the spring neap cycle. The entire Delta responds more or less in unison at these frequencies, and a substantial flux of water is needed to supply the volume that is occupied or drained. The subtidal oscillations in Figure 2 are probably exaggerated for reasons explained in Section 3 but the plot gives a correct impression that these variations are very substantial. The magnitude of the oscillations is site-specific, varying with the amount of upstream tidal prism that has to be filled. Figure 3 shows modeled differences in subtidal fluctuations at Martinez, Chipps Island and the four outflow stations using the DSM2 model.

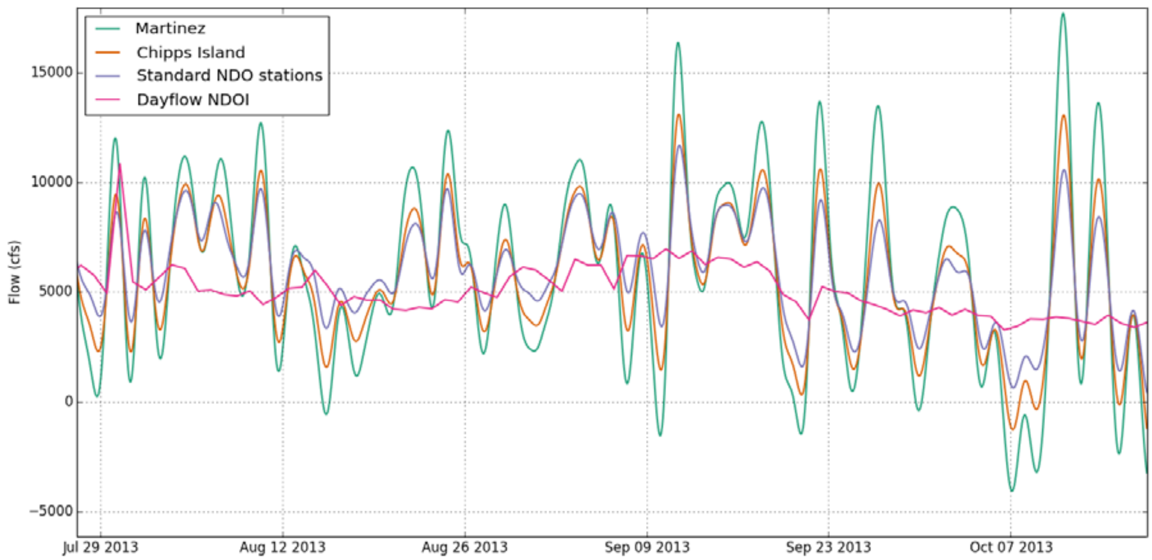


Figure 3: DSM2 modeled flows corresponding to three possible NDO nominal locations. Dayflow NDOI is shown for reference.

In contrast with NDO, NDOI is mostly non-tidal. NDOI is constructed from upstream flows and thus effectively ignores not only the semi-diurnal and diurnal tides but also most of their itinerant effects like filling and draining. NDOI can be thought of as an abstract undercurrent that applies equally well along the length of the estuary. This notion of a "river" undercurrent is common in conceptual models of estuarine systems. NDOI is related to NDO in that they should balance in an average sense over the medium term -- as the model results do in Figure 3.

Neither index fits all applications and contexts. At DWR we regularly make reference to subtidal fluxes in our analyses. Filling and draining is particularly relevant in the chain of events bringing salt into the mid-Delta. Still, when it comes to expositional clarity and general utility for regulatory purposes, NDOI has much to recommend it instead of NDO calculated from the four flow stations (Dutch Slough, Jersey Point, Rio Vista and Threemile Slough)

1. Existing ecological results are based on NDOI. There is no obvious reason why the higher frequency subtidal component added by observed NDO could improve these, or if it could why the current four flow monitoring sites would be appropriate. Downstream locations are wider and even harder for accurate measurements.
2. Observed NDO cannot be interpreted easily with the human eye. If the oscillations turn out to be a nuisance in a management context, which they almost certainly will be, filtering them will filter the upstream part of the signal as well, including the contributions of flows, exports and consumptive use. What began as an attempt to refine may end in coarsening.
3. Much of the filling and draining is caused by offshore events with a short prediction window compared to travel time from Oroville and Shasta. These oscillations are a natural variation that cannot be resisted or negated with flow from upstream. DWR is wary of the operational practicability of any short term standards that includes this information.
4. NDOI is amenable to planning applications -- given a hydrology, export, climate and land use pattern, DWR can produce a credible approximation of NDOI. This is not feasible with NDO.

5. NDO requires some expertise to calculate and interpret. As an example of what can be of concern, sometimes NDO can be computed from daily averages. Daily (24-hour) sampling of a strong 25 hour signal will distort the signal through a signal processing artifact called "aliasing". The difference can be noted by comparing the yellow line (daily average) and green line (cosine-Lanczos filter) in Figure 2. The absolute magnitude of the differences reaches 5-10,000 cfs, at times, which means that common signal processing errors could be as large as the present notion of summer outflow.

1.2.2 Accuracy

Both NDO and NDOI contain significant error. From Figure 2, it should be clear that uncertainty is an issue with one or both outflow estimates, since NDO and NDOI should be vertically centered with one another and yet in practice they differ by 6,000 cfs. Although the discrepancy doesn't evolve much over the period covered by this plot, it is nonstationary in sign and magnitude over seasons and years. On the average (1997-2015, considering flows under 20,000cfs) NDOI is lower than NDO by 2000cfs, but this average includes long swings in both directions that are much larger. To the extent that we have been able to check (including 2013 and 2015), most of the big clashes between NDO and NDOI are mirrored by similar mass conservation inconsistencies between the four NDO stations and their immediate upstream neighbors, suggesting that biases in subtidal flow at the four stations are the major source of discrepancy. In Section 3, we detail a fairly tight control volume check using drought stations installed in 2015 around Rio Vista which demonstrate the severity of the problem around that station and show not only very substantial mean closure error but also over-amplification of subtidal oscillations. We also explain in that section why such errors would be an unsurprising consequence of the way flow stations are set up and calibrated in the Delta using acoustic Doppler current profilers and the index velocity method.

Even without elaborate volumetric checks, we feel it is evident just from inspection that NDO in Figure 2 is implausibly high and a similar situation prevailed in most of the summers in the early 2000s. There is no credible source for thousands of cubic feet per second of persistent bonus outflow the plot implies all season long. An extra surface flow of 6,000cfs would be conspicuous – this is the same size as a medium size Sierra river in spring. Alternatively, consumptive use would have to be negative all summer, reaching 6,000 cfs of channel accretion in fall. Or the projects would have to report exports and then not pump.

In contrast, the accuracy issues with NDOI are substantial, but easier to explain physically and also more bound in magnitude. NDOI is a lumbering algebraic calculation with many inputs. Most of the major upstream flows and exports are known with some accuracy, but there are always questions concerning the completeness of the list of inflows and we have reservations whether the Yolo component of flow reaches the tidal Delta in summer and supports beneficial use. The most nagging issue with NDOI is the uncertainty over channel depletions and consumptive use, which is a major impetus of this document. The channel depletions are estimates based on data concerning land use and farming practices and there could be variations from historical conditions. Section 2 describes how consumptive use and net channel depletions are estimated.

We want to close this section by pointing out that our remarks about NDO accuracy apply only to the four station approach, which is a sparse computation based on some of the widest monitoring locations in the Delta. We do think there is information content in all the gages and in Section 3.2 we will describe techniques in development that better utilize the entire USGS-DWR flow network and consider the structural characteristics of flow measurement bias to our advantage.

2 Delta Consumptive Use and Channel Depletion

2.1 Delta Consumptive Use and Channel Depletion

Diversions of water onto agricultural lands for irrigation are not metered and are difficult to measure because the diversions are made through siphons, pumps, and floodgates operating under continuously fluctuating water levels in Delta channels. These diversions are withdrawn at more than 1,800 locations in the Delta (California Department of Water Resources, 1995). Some areas of the Delta, namely Delta lowlands (areas of the Delta below the 5-foot mean sea level contour), receive seepage from adjacent channels. Seepage onto islands in the Delta lowlands contributes to channel depletion but is not directly measureable. For these reasons, most estimates of Delta channel depletions are based on estimates of crop water demands (crop evapotranspiration, ET) and the sources of water to meet these demands. The main sources consist of: applied water (I_A), soil moisture (SM) and precipitation (PPT). Within the Delta lowlands, seepage (S) of water from adjacent Delta channels is also a source. Also common in the lowlands is the leaching salts from the root zone through large irrigation applications. Typically, leach water (LW_A) is applied from October through December and drained (LW_D) from January through April. Excess water is pumped from the Delta islands back into the Delta. This water consists of excess irrigation water (I_D), leach water (LW_D), and surface runoff (RO) from precipitation.

As described in DAYFLOW documentation (California Department of Water Resources, 2015), Delta consumptive use is synonymous with gross channel depletions. Net channel depletions are the difference between total diversions (DIV) and total drainage or return flows (RET). Net channel depletions are the same as gross channel depletions less Delta precipitation. These relationships are defined by Equations 1 through 5 and graphically shown in Figure 4 below.

$$\text{ET} = \text{Gross Channel Depletion} \quad \text{Eqn. 1}$$

$$\text{Gross Channel Depletion} = \text{DIV} + \text{S} + \text{PPT} + \text{SM} - \text{RET} \quad \text{Eqn. 2}$$

$$\text{DIV} = I_A + LW_A + S \quad \text{Eqn. 3}$$

$$\text{RET} = I_D + LW_D + RO \quad \text{Eqn. 4}$$

$$\text{Net Channel Depletion} = \text{DIV} - \text{RET} \quad \text{Eqn. 5}$$

The models for estimating Delta channel depletions vary in the degree in which key factors are simplified. These assumptions will affect any estimation of Delta outflow based in part on simulated channel depletions. These models, discussed below are DAYFLOW and Delta Island Consumptive Use Model (DICU). Also presented is the model which will replace DICU for Delta modeling, the Delta Evapotranspiration of Applied Water Model (DETAW). Lastly presented are differences between DAYFLOW, DICU and DETAW in Delta precipitation, net Delta channel depletion, and Delta outflow.

The current models estimating channel depletions assume Delta channels are not hydraulically connected to ground water. Thus seepage is assumed to directly deplete adjacent channels and does not replenish ground water. Seasonal mining and replenishing of groundwater in the Delta could be a significant factor in actual Delta outflow. DWR analysis of historical salinity and calculated Delta outflow indicates that in several years, compared to current models' estimates of Delta outflow, actual outflow may be somewhat higher during the irrigation season and lower during winter months. A brief literature review of Delta groundwater is presented at the end of this section on Delta channel depletions.

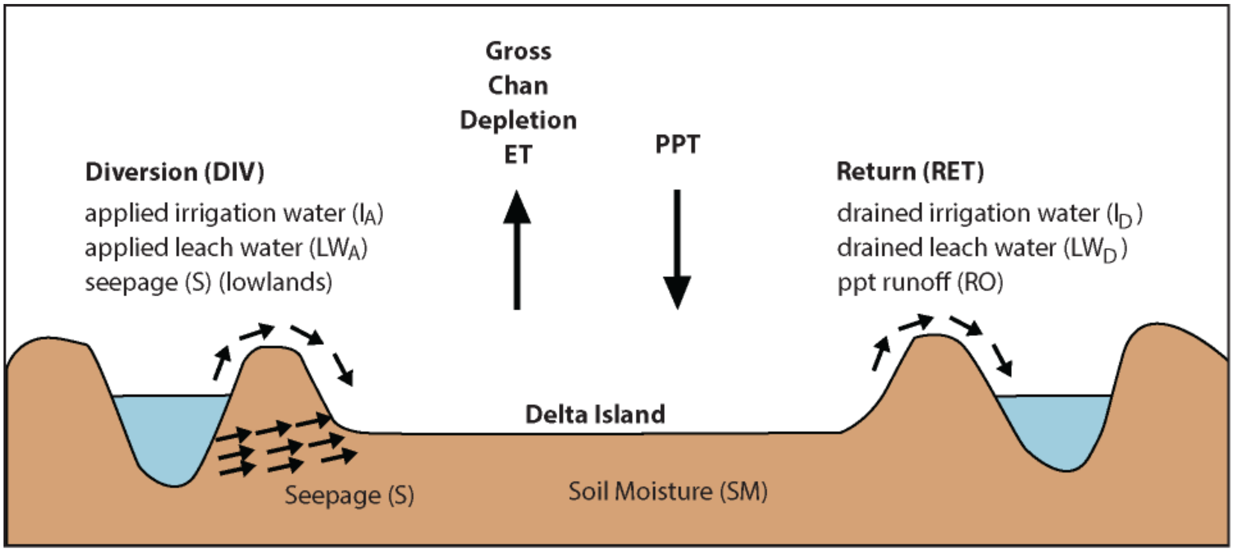


Figure 4: Schematic showing the water balance for Delta Islands

2.2 DAYFLOW

DAYFLOW is a computer program developed in 1978 as an accounting tool for determining historical Delta boundary hydrology (California Department of Water Resources, 2015). Given that the Delta is short compared to the propagation speed of system changes (hydraulic changes such as tides and floods traverse the Delta in 3-4 hours), flows are not lagged or routed to account for travel time.

Net Delta outflow is estimated by performing a water balance about the boundary of the Sacramento-San Joaquin Delta, nominally taking Chipps Island as the western limit. The calculation for Delta Outflow Index (NDOI) includes estimated daily net Delta-wide channel depletions:

QCD = QGCD – QPREC, where:

QCD is daily net Delta-wide channel depletion,

QGCD is daily gross Delta-wide channel depletion, and

QPREC is daily Delta-wide runoff from precipitation.

As shown in Figure 5, daily Delta-wide gross channel depletions are based on a curve fitted through monthly values that were developed by DWR in a 1965 study (California Department of Water Resources, 2015). DAYFLOW documentation fails to include any more details about the origin of the monthly gross channel depletion values. However, a 1962 DWR bulletin presented monthly Delta consumptive use based on crop surveys and experimentally-derived unit values of consumptive use of water for many of the crops grown in the Delta (California Department of Water Resources, 1962). While this report did not present Delta channel depletions, it did discuss how changes in soil moisture and groundwater storage might be estimated in order to assess channel depletion.

A DWR office report in June of 1965 presented Delta land use acreage for each of 86 Delta reclamation districts (California Department of Water Resources, 1965). These values were based on land use surveys in 1957, 1958, and 1961. It is likely that the 1965 DWR study mentioned in DAYFLOW documentation was based on unit crop water use values, land use surveys, and some estimation of seasonal patterns changes in soil moisture and groundwater storage.

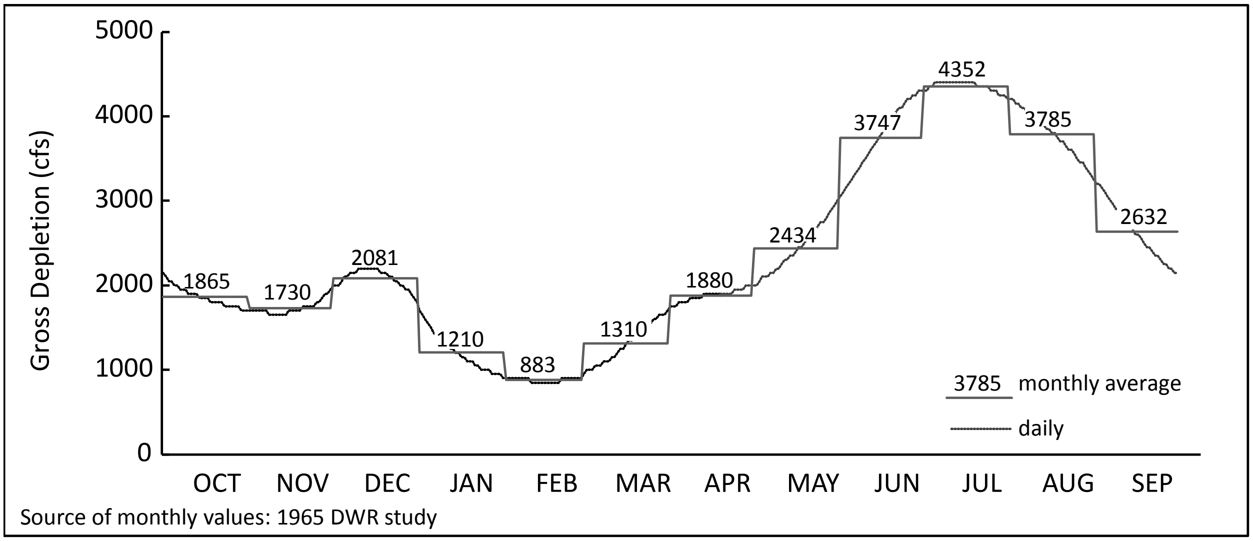


Figure 5: Yearly Repeating Seasonal Pattern of Gross Channel Depletions Assumed in DAYFLOW

Daily Delta-wide volume of precipitation is estimated by applying daily precipitation at Stockton Fire Station Number 4 to the total delta acreage (California Department of Water Resources, 2015). Total daily Delta runoff flow is then estimated by distributing this volume of water evenly over five days, the day the precipitation was recorded and the following four days (Figure 6).

Key features in DAYFLOW's estimation of daily net Delta channel depletions are:

1. Net Delta channel depletions are based on 12 monthly values of total gross Delta depletions developed by DWR in a 1965 study. These were likely based on land use surveys in the late 1950s and early 1960s and unit crop use values of some kind. They likely incorporate some accounting of change in soil moisture and groundwater storage in the Delta.
2. Monthly gross Delta depletions are repeated each year. This corresponds to assuming both Delta land use and factors which determine monthly patterns of crop evapotranspiration are constant for all years. Net Delta channel depletions are calculated using precipitation at Stockton Fire Station No. 4, applying it to the entire Delta and then assuming the precipitation is available to meet Delta consumptive use demands.

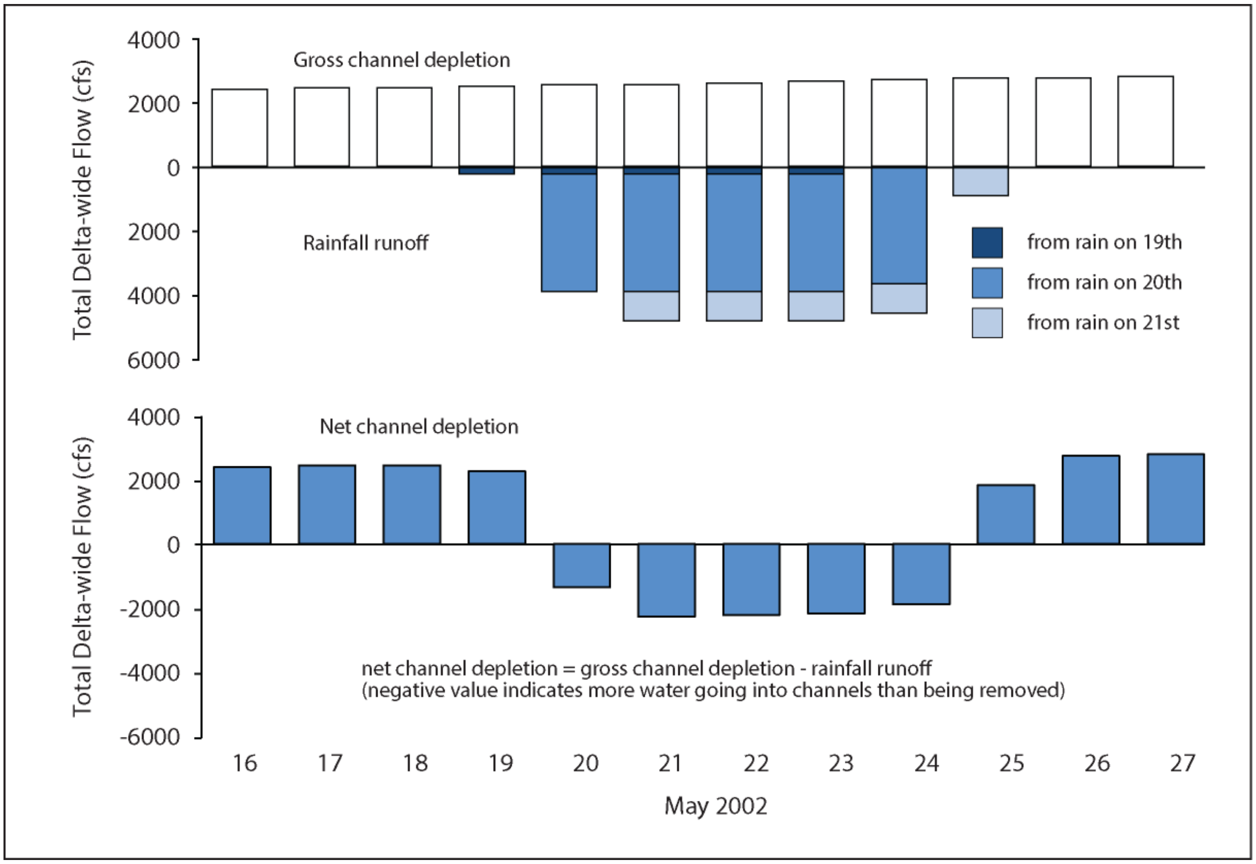


Figure 6: Example of DAYFLOW estimation of net channel depletion

2.3 Delta Island Consumptive Use Model

The Delta Island Consumptive Use Model (DICU) is currently the model used by DWR to generate Delta agriculture diversions and drainage needed for simulation of Delta hydrodynamics and water quality. DICU is based on DWR's earlier Consumptive Use (CU) models for Delta uplands and lowlands which provide the Delta channel depletion used by DWR's water resources planning model (currently CALSIM II). DICU was developed to improve estimates of Delta channel depletion compared to DAYFLOW and while refining the modeling of Delta conditions by accounting for the spatial variance of Delta channel depletion in addition to the temporal patterns due to irrigation seasons (California Department of Water Resources, 1995).

DICU estimates, on a monthly basis, the water that enters, leaves, or is stored on each of 142 Delta subareas. Factors considered in tracking water are: land use, plant rooting depths, seepage, soil moisture, irrigation season, evapotranspiration, and precipitation.

Land use is categorized according to 20 types and based on historical surveys. Currently two land use patterns are used in simulating historical conditions with DWR's Delta Simulation Model II (DSM2): a critical year and a non-critical year (California Department of Water Resources, 1995). The critical year Delta land use is based on a 1976 survey and is assumed for any critical or dry year, and the non-critical year Delta land use is based on surveys in the late 1970s and early 1980s and is assumed for all non-critical or non-dry years (California Department of Water Resources, 1994). Some differences between the two land use patterns used are shown in Figure 7.

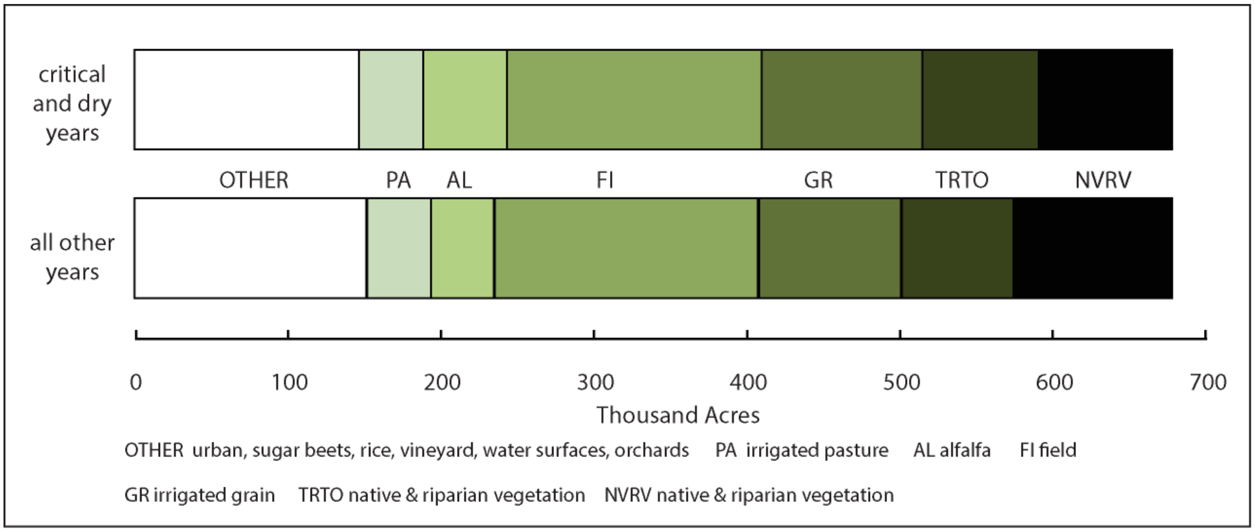


Figure 7: Delta land use areas used in DICU for critical and dry years versus all other years.

DICU tracks subarea soil moisture and estimates the amount of water in the soil available to plants. Soil moisture limits in DICU are based on extensive DWR neutron probe measurements of Delta islands in the 1960s (California Department of Water Resources, 1995). DICU assumes maximum soil moisture level in Delta lowlands to be 3 inches per foot rooting depth and 1.5 inches per foot rooting depth in the Delta uplands. This difference is due to mainly peat soils in the lowlands and sand and alluvial soils in the uplands. Month-end minimum soil moisture levels are assumed that recreate an observed yearly pattern of Delta soils being near capacity at the beginning of the irrigation season, then the moisture in the soil is mined, before approaching wilting point at the end of the season. Crop root depths vary by crop and by whether an island is in uplands or lowlands.

DICU assumes one of two types of irrigation seasons, depending up whether the year is a dry or critical year versus all other types of years. Each of the crop types has its own irrigation season.

Delta evapotranspiration (ET) estimated in DICU is based on pan evaporation and monthly unit ET by crop.

$$ET_{(\text{crop, month, year})} = \left(\begin{array}{c}\text{total monthly}\\ \text{unit ET per crop}\\ \text{(crop, month)}\end{array}\right)\left(\frac{\begin{array}{c}\text{pan evaporation}\\ \text{at Manteca}\\ \text{(month, year)}\end{array}}{\begin{array}{c}\text{long-term average}\\ \text{pan evaporation at}\\ \text{Davis (month)}\end{array}}\right) \qquad \text{Eqn 6}$$

Long-term ET values by crop and month are based on various studies in the 1970s and 1980s. Long-term average pan evaporation by month is based on data from two sites in Davis, California for the 1956 to 1984 period. Pan evaporation for any given historical month and year to use in Equation 6 come from reported pan evaporation from Manteca, California.

For subareas in Delta lowlands, the DICU model simulates the practice of applying water during winter months to leach salts from the root zone. Timing and volume of leach water are based on a 1981 DWR study (California Department of Water Resources, 1995). Monthly Delta-wide leach volumes and later drainage are proportionally distributed among subareas based on subarea acreage (Figure 8).

Precipitation on each of the 142 sub-areas is determined by weighting the precipitation of five Delta stations using a Theissen Polygon interpolation routine (Figure 9). Originally seven stations were used, but now one station (Galt) assumes values from an adjacent station (Lodi). For sub-areas spanning two or more polygons, the precipitation is determined proportionally by area. Operating on a monthly time-step, DICU assumes that total precipitation for a month is available to plants for that entire month. For example, any rainfall occurring at the end of a month is assumed available to meet crop ET demands for the entire month. (This can cause underestimation of excess precipitation and runoff, particularly large, sporadic events).

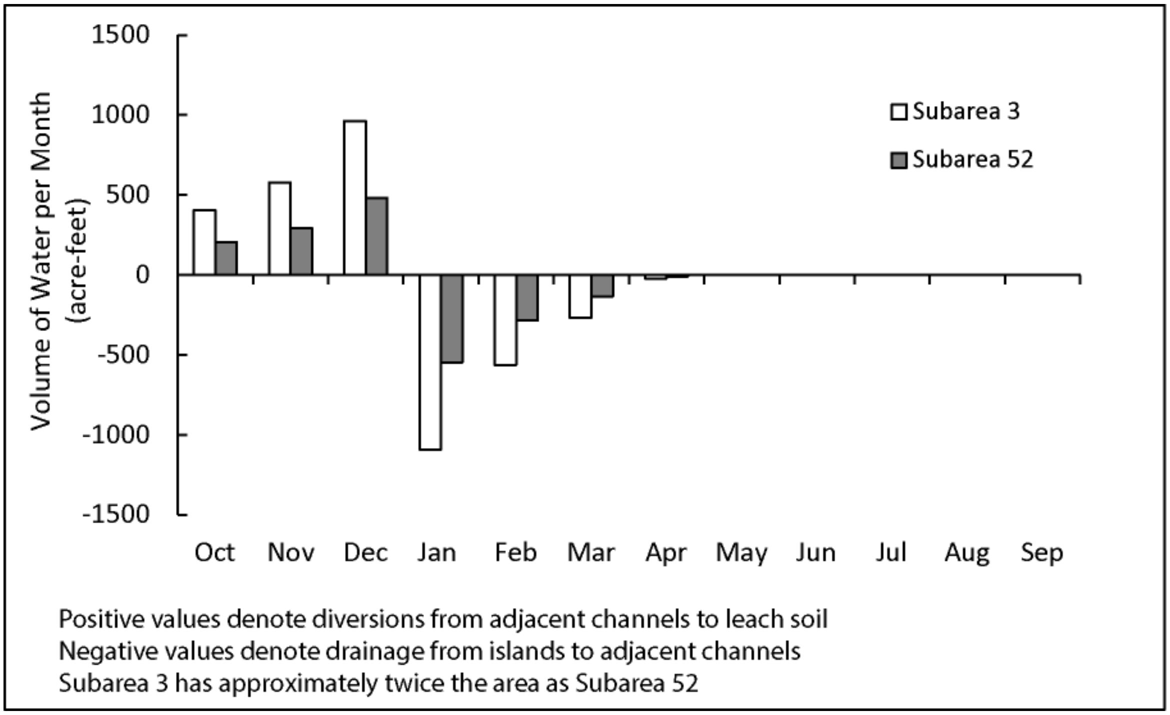


Figure 8: Example of leaching volume and seasonal variation assumed in DICU

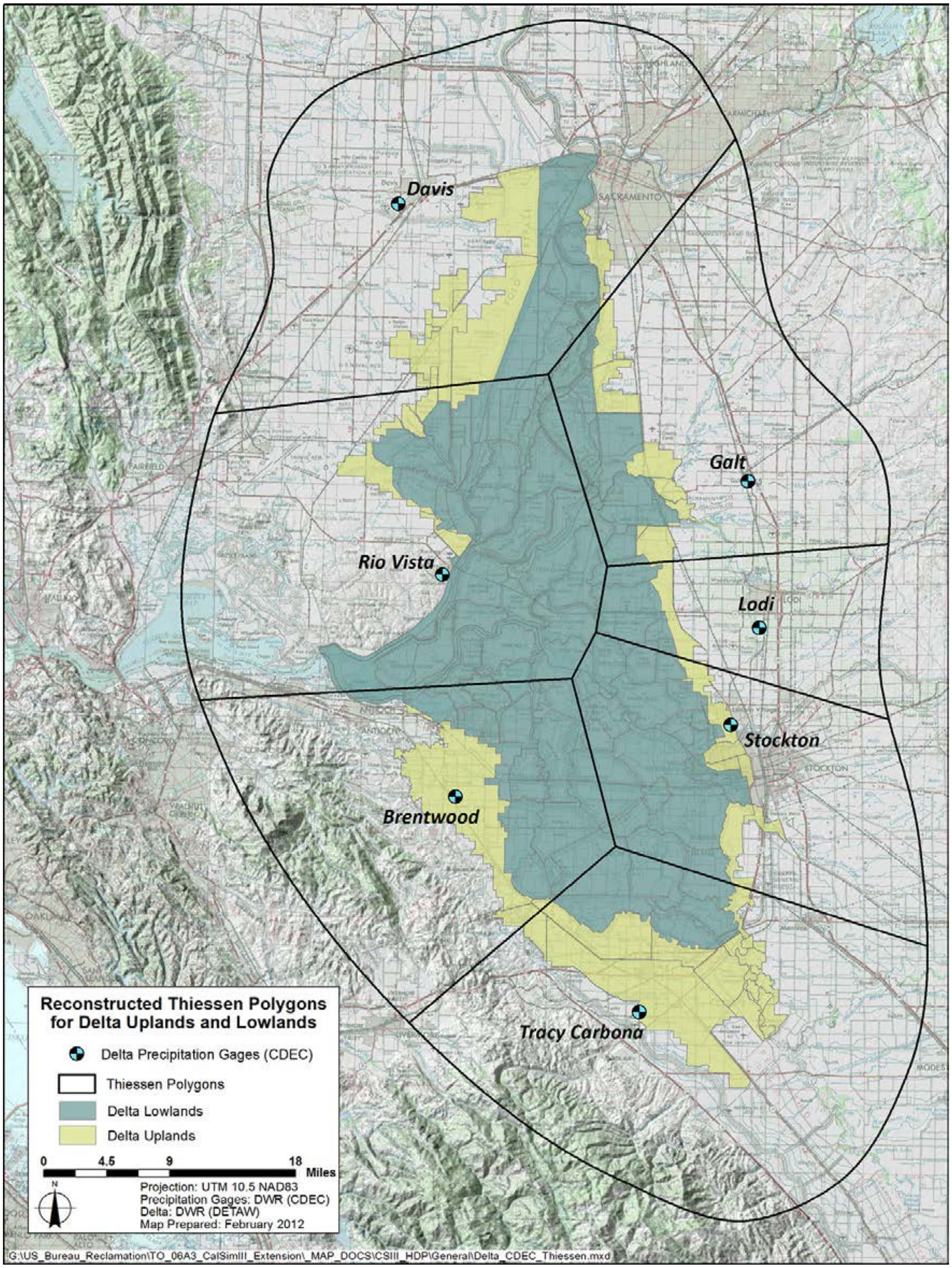


Figure 9: Theissen Polygon and precipitation stations used in DICU to estimate Delta-wide precipitation

2.4 Delta Evapotranspiration of Applied Water Model

In 2006 the Delta Evapotranspiration of Applied Water model (DETAW) was developed by the University of California (UC) at Davis to better estimate consumptive water demands within the Delta (Kadir, 2006). DETAW, in contrast to DICU, runs on a daily time step and therefore used daily values of unit consumptive use and precipitation. So due to the daily time step, DETAW can reproduce large, sporadic runoff events both in terms of runoff volume and salinity response which is not available in DICU. Also different from DICU, DETAW has been calibrated and validated based on independent estimates of Delta net consumptive use as briefly described below.

DETAW estimates consumptive water demands for 168 subareas within the Delta Service Area (Figure 10). As in the DICU, daily precipitation for each subarea is estimated from seven precipitation gaging stations in and adjacent to the Delta and areal weighting factors calculated from Thiessen polygons. Daily potential ET rates, ETo, are computed using the temperature based Hargreaves-Samani equation calibrated to local Delta conditions (Kadir, 2006). The equation is calibrated to ETo values calculated for nine California Irrigation Management Information System (CIMIS) stations determined using the modified Penman-Monteith equation. Daily crop ET unit rates are computed using seasonal crop coefficient curves. Daily water balances are used to estimate daily ET of applied water by subarea. Irrigations (diversions from Delta channels) are triggered when the soil moisture content drops below a specified threshold after accounting for effective precipitation and seepage.

DETAW was calibrated using distributed ET data for the Delta developed with the model Surface Energy Balance Algorithm for Land (SEBAL) for 2007 (Figure 11). SEBAL uses satellite-based measurements and energy balance models to estimate the spatiotemporal distribution of actual ET (Davids Engineering, Inc., 2012). When used in conjunction with spatial land use data, SEBAL can provide estimates of actual ET by crop type. DETAW was then validated using 2009 SEBAL-based Delta ET (Figure 12).

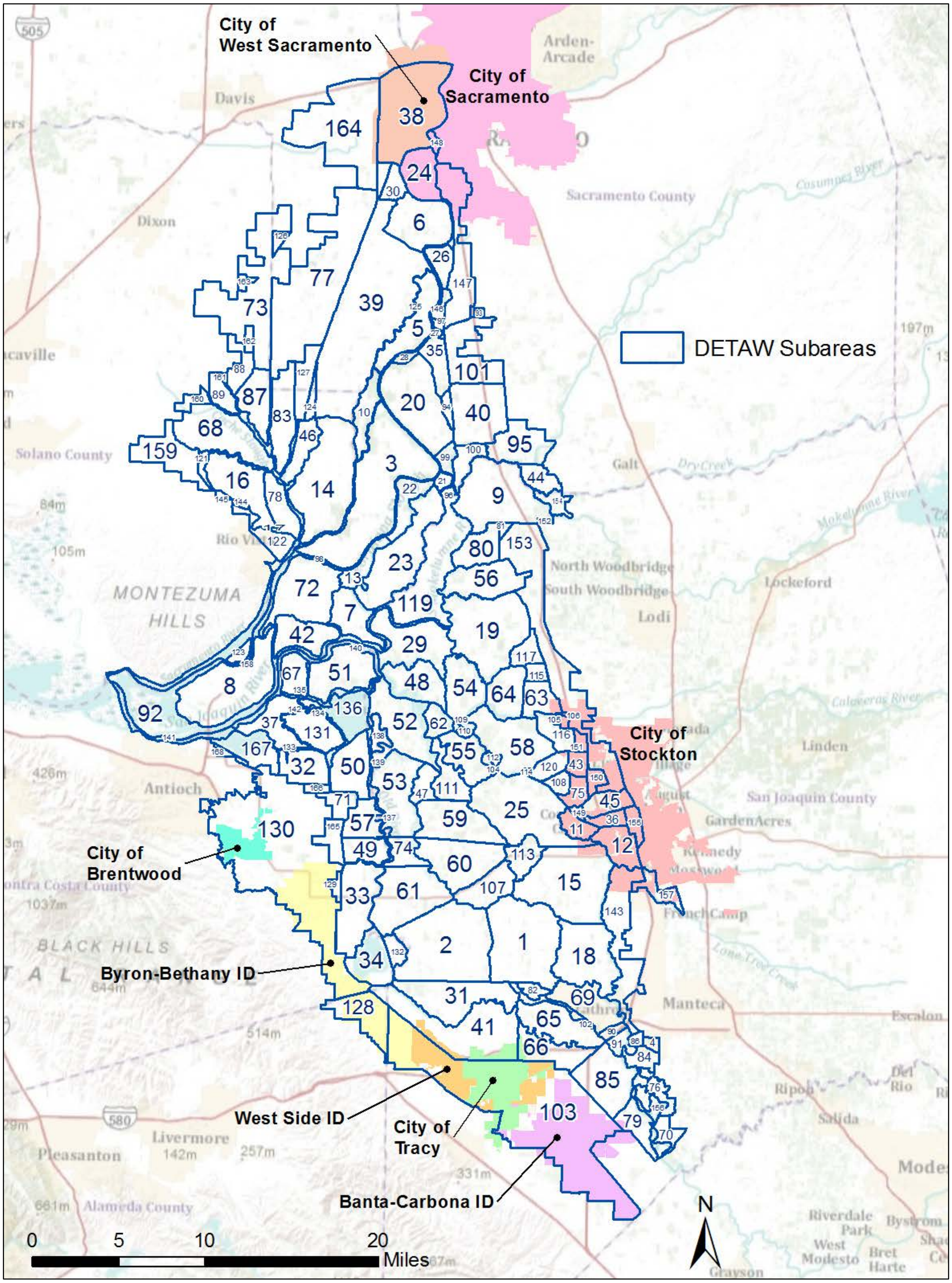


Figure 10: DETAW Model Consumptive Use Subareas

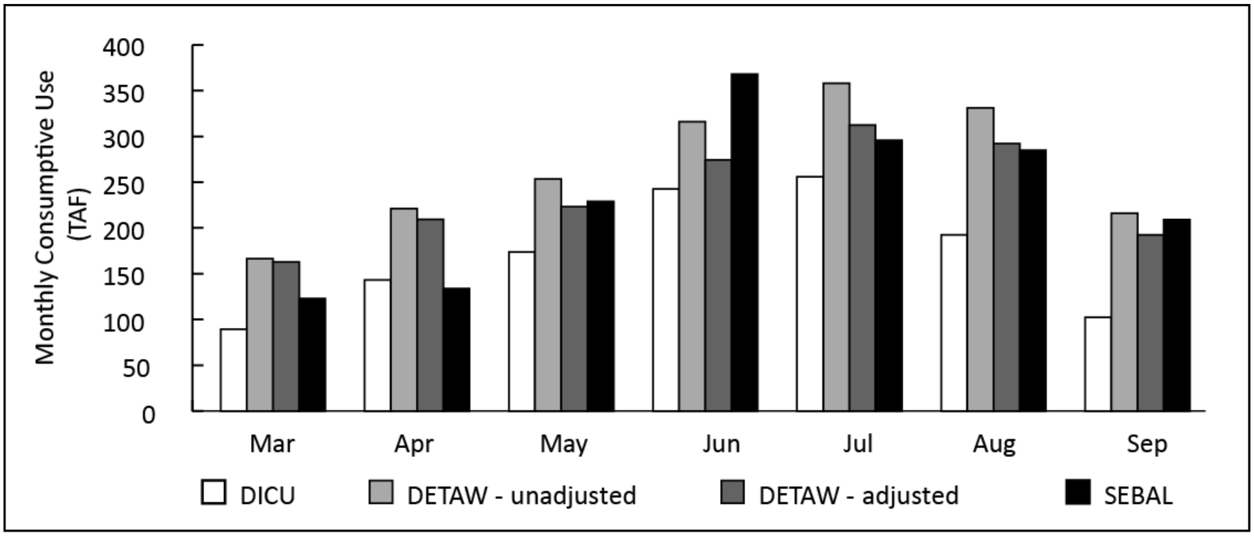


Figure 11: Calibration of DETAW crop coefficients to Match SEBAL Consumptive Use, 2007

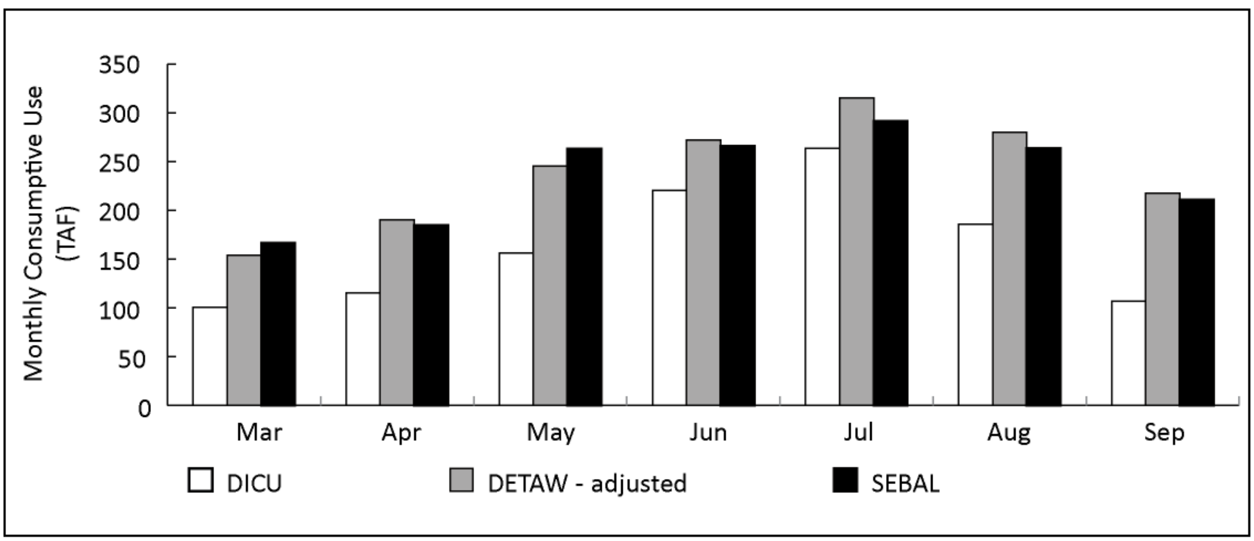


Figure 12: Validation of DETAW crop coefficients to SEBAL, 2009

2.5 Groundwater as a Source of Water to Meet Delta Consumptive Use

The current models estimating channel depletions assume Delta channels are not hydraulically connected to ground water. Anecdotal evidence of groundwater use in the Delta lowlands, an area subject to significant subsidence over time due primarily to oxidation and tilling of organic soils, is the claim that some farmers irrigate crops through managing the water table depth rather than diverting water from adjacent channels. If groundwater is being used to meet some portion of crop water demands, then actual Delta outflow may be higher during the irrigation season than is currently estimated through NDOI. In order to determine how much seepage from the channels to the ground water system takes place, or how much ground water enters or leaves the Delta boundary, additional information, data and a model will need to be applied that simulates groundwater, surface water, stream-groundwater interaction, and other components of the hydrologic system, such as DWR's Integrated Water Flow Model (IWFM).

A search of past studies and reports finds several references related to the issue of groundwater use in Delta. A 1956 DWR report presents analysis based on field investigations from May 1954 through October 1955 (California Department of Water Resources, 1956). The study included: determining the amount of water applied on sample fields for major crops in the Delta Lowlands, conducting mineral analysis of water samples from drains and Delta channels, determining the quantity of water applied to the Delta lowlands, determining the concentration of dissolved minerals in surface waters and in drains, and quantifying net degradation of water in Delta channels due to saline drainage water from Delta islands. The report estimated water supply and disposal in Delta lowlands (Figure 13). Water supply consisted of estimates of applied water and precipitation. Water disposal consisted of drainage and consumptive use. To balance the system, supply should equal disposal, however during the 1953 and 1954 irrigation season, disposal was significantly larger than supply. The report concluded that some combination of seepage and groundwater was unaccounted. If all of the unaccounted water is assumed to be seepage, seepage contribution would far exceed current assumptions in Delta models, implying that groundwater was a source of water for Delta lowlands.

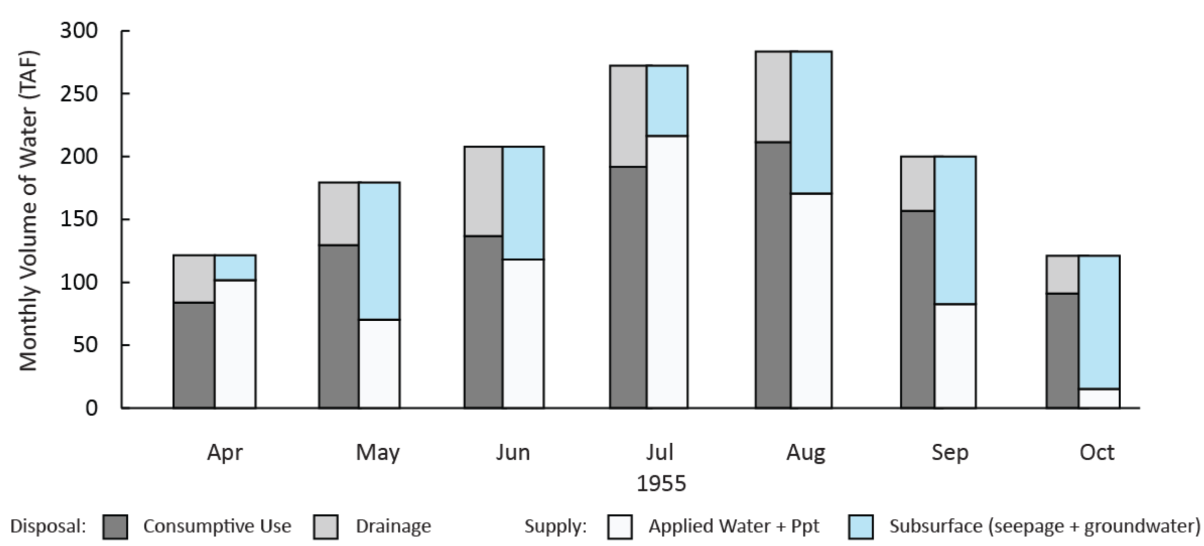


Figure 13: Water Supply and Disposal for Delta Lowlands Reported in DWR Report 4 (1956).

A 1956 DWR report estimated contributions to MacDonald Island waters from assumed sources (California Department of Water Resources, 1956). Using mineral analysis of water samples taken from island drains and piezometers, the report concluded that in general 80 percent of groundwater came from contiguous channel water, 18 percent from Mokelumne River area groundwater, and 2 percent connate water (Figure 14). A similar DWR report in 1959 for McDonald Island (California Department of Water Resources, 1959) found similar percentages, the channel water coming from the San Joaquin River (Figure 15).

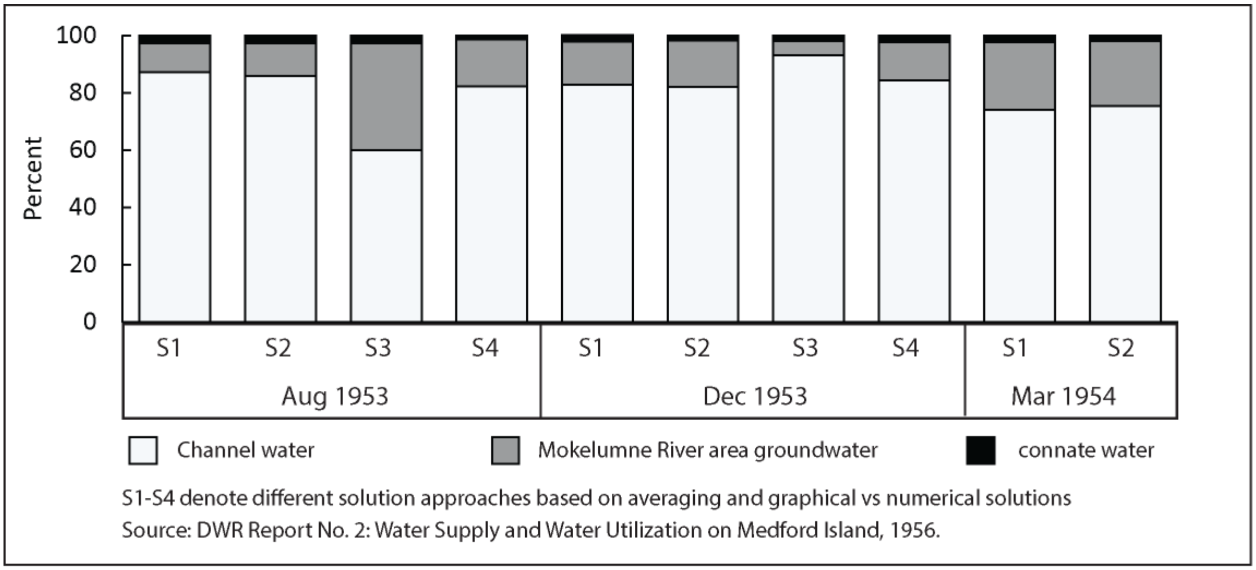


Figure 14: Estimated Contributions to Medford Island Groundwater from Assumed Sources.

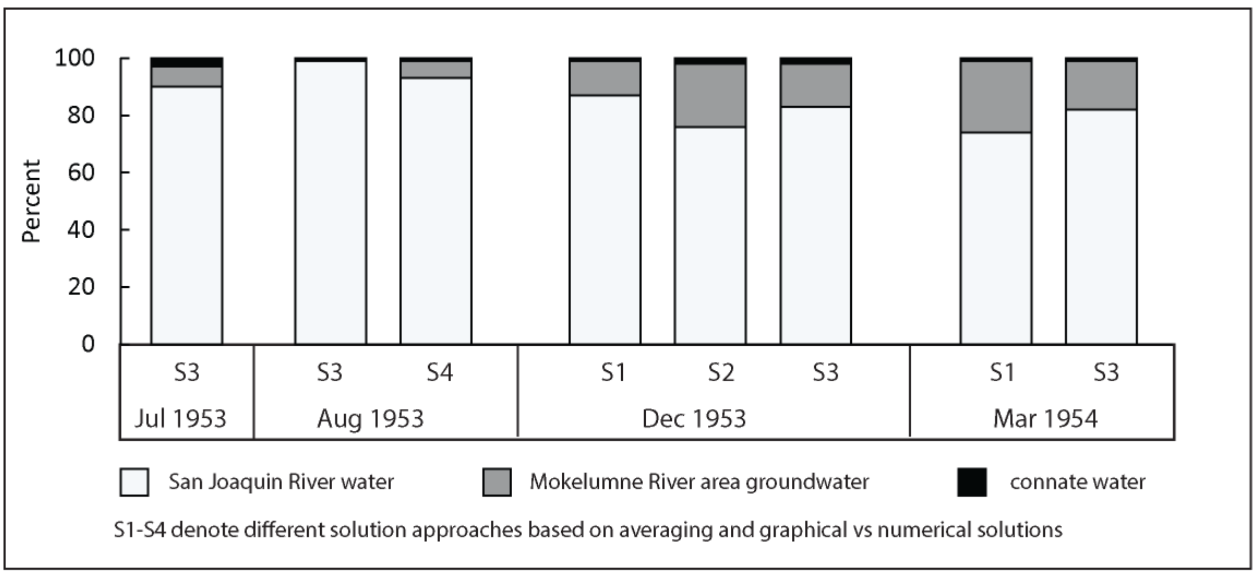
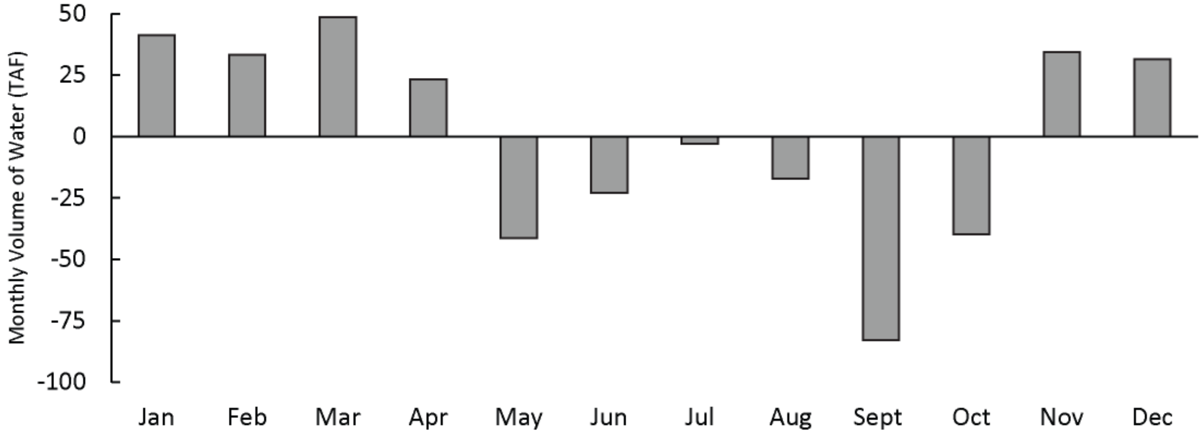


Figure 15: Estimated Contributions to McDonald Island Groundwater from Assumed Sources

A 1962 DWR report, Salinity Incursion and Water Resources, Appendix to Bulletin 76, Preliminary Edition estimated historical Delta outflow for October 1921 through September 1957 (California Department of Water Resources, 1962). Variations in patterns of salinity incursion and Delta outflow were attributed to changes in soil moisture and groundwater. Assuming change in groundwater over one year is zero, monthly rates of change in groundwater storage were determined using a mass diagram. The results indicated that during May through October water was leaving groundwater storage in Delta lowlands and replenishing groundwater in the other months (Figure 16).



Note: positive values denoter groundwater being replenished, negative values denote groundwater being mined
Source: Appendix to Bulletin No. 76: Salinity Incursion and Water Resources, DWR 1962.

Figure 16: Estimated monthly rate of change in groundwater storage within Delta Lowlands.

2.6 Comparison of key results from DAYFLOW, DICU, and DETAW models

Key model output from historical simulations with DAYFLOW, DICU, and DETAW was compared. DAYFLOW data came from its website (California Department of Water Resources, 2015) while DICU and DETAW data are output from current historical simulations by the Delta Modeling Section of DWR. **Note that results do not account for groundwater but assume all water needed to meet crop needs is net channel depletions.** Figure 17 and Figure 18 compare long-term monthly averaged Delta-wide precipitation, Delta channel depletion, and Delta outflow under the three models. Figure 19 and Figure 20 compare daily Delta channel depletions and net Delta outflow for 2014.

Figure 20 shows that when DICU and DETAW are compared to DAYFLOW during the irrigation season, DICU generates lower total consumptive use and higher NDOI while DETAW generates higher total consumptive use and lower NDOI in June and July.

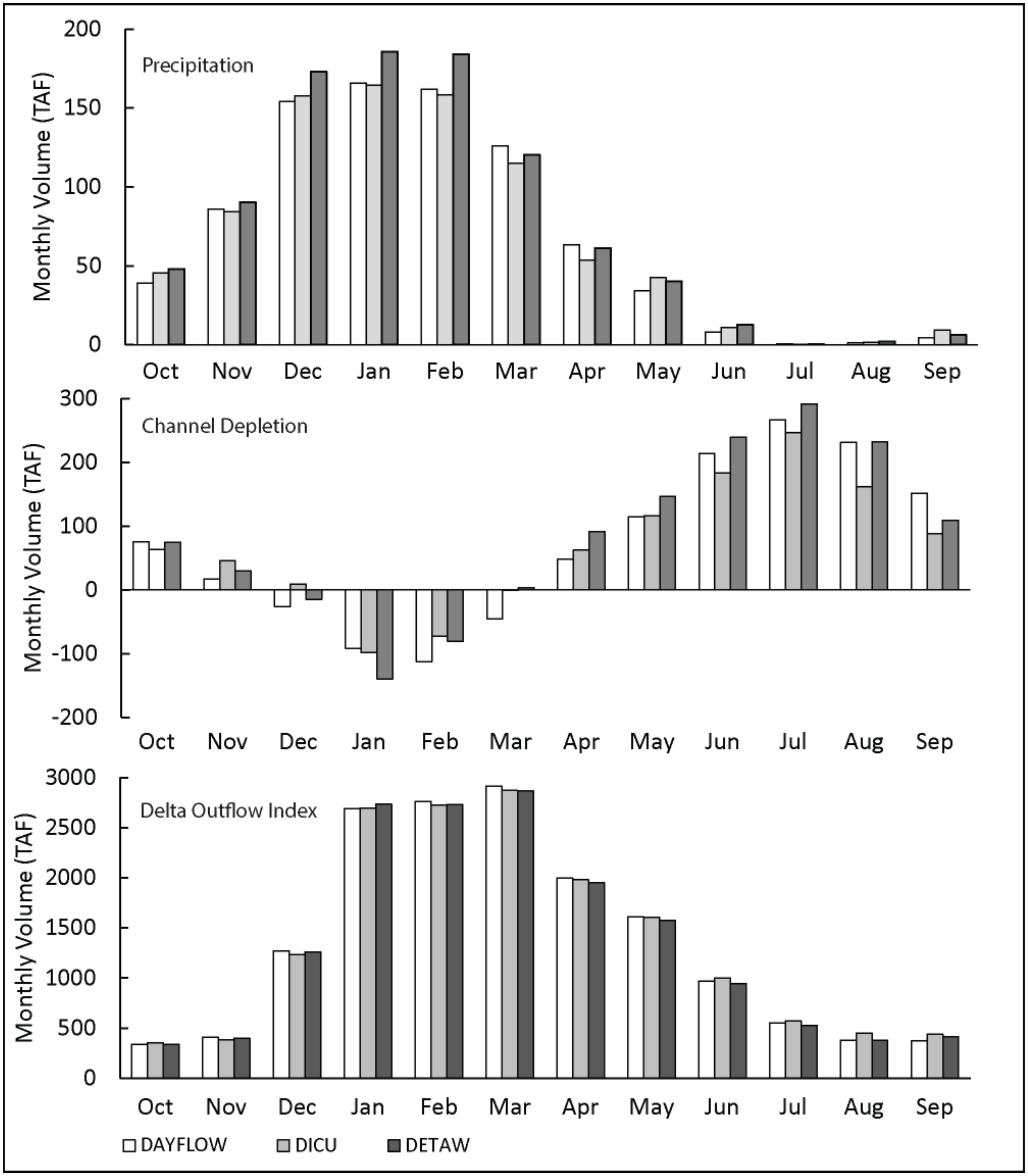


Figure 17: Key Long-Term Monthly Average Volumes for Oct – Sep, 1990 – 2014

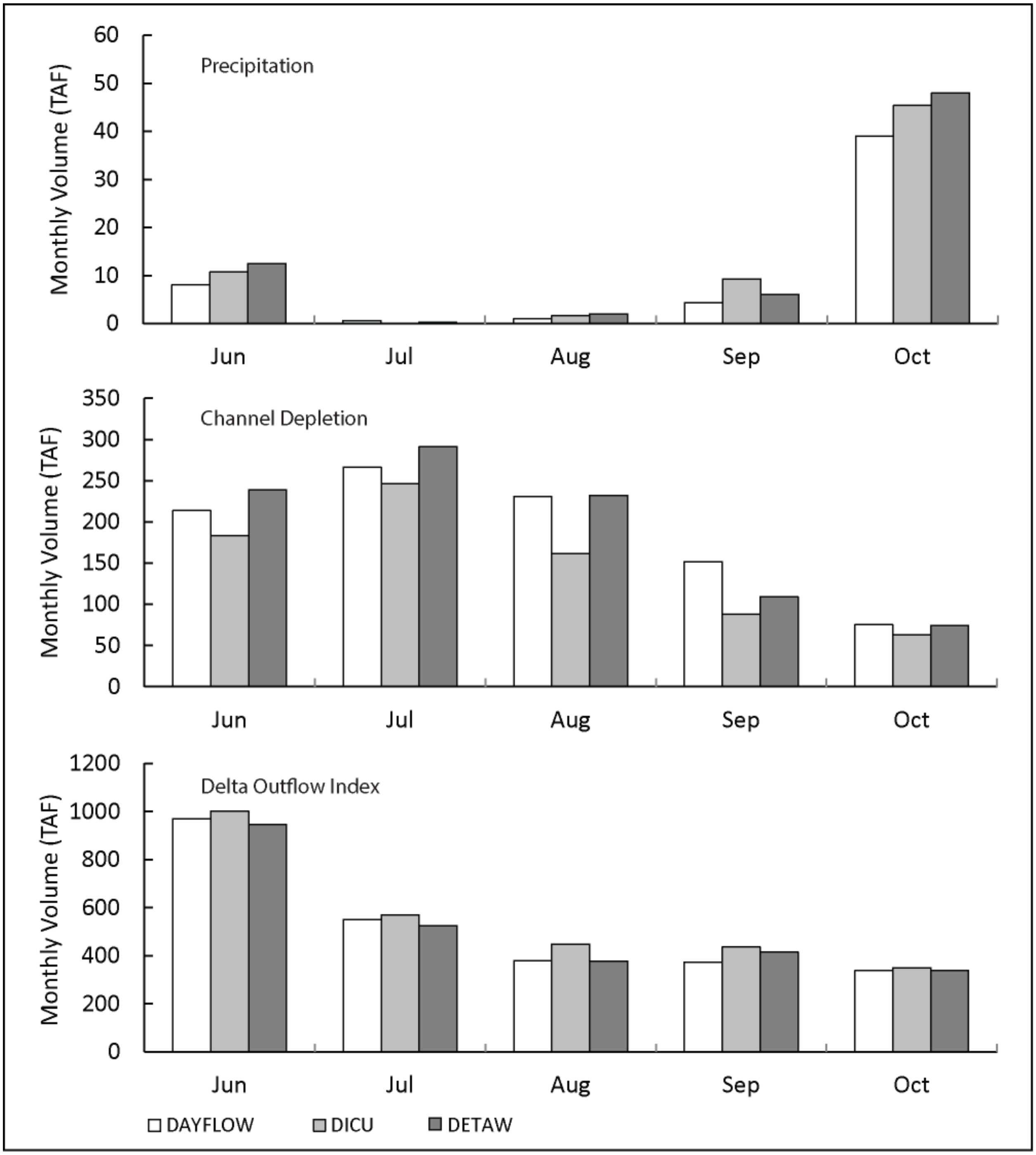


Figure 18: Key Long-Term Monthly Average Volumes for Jun – Oct, 1990 – 2014

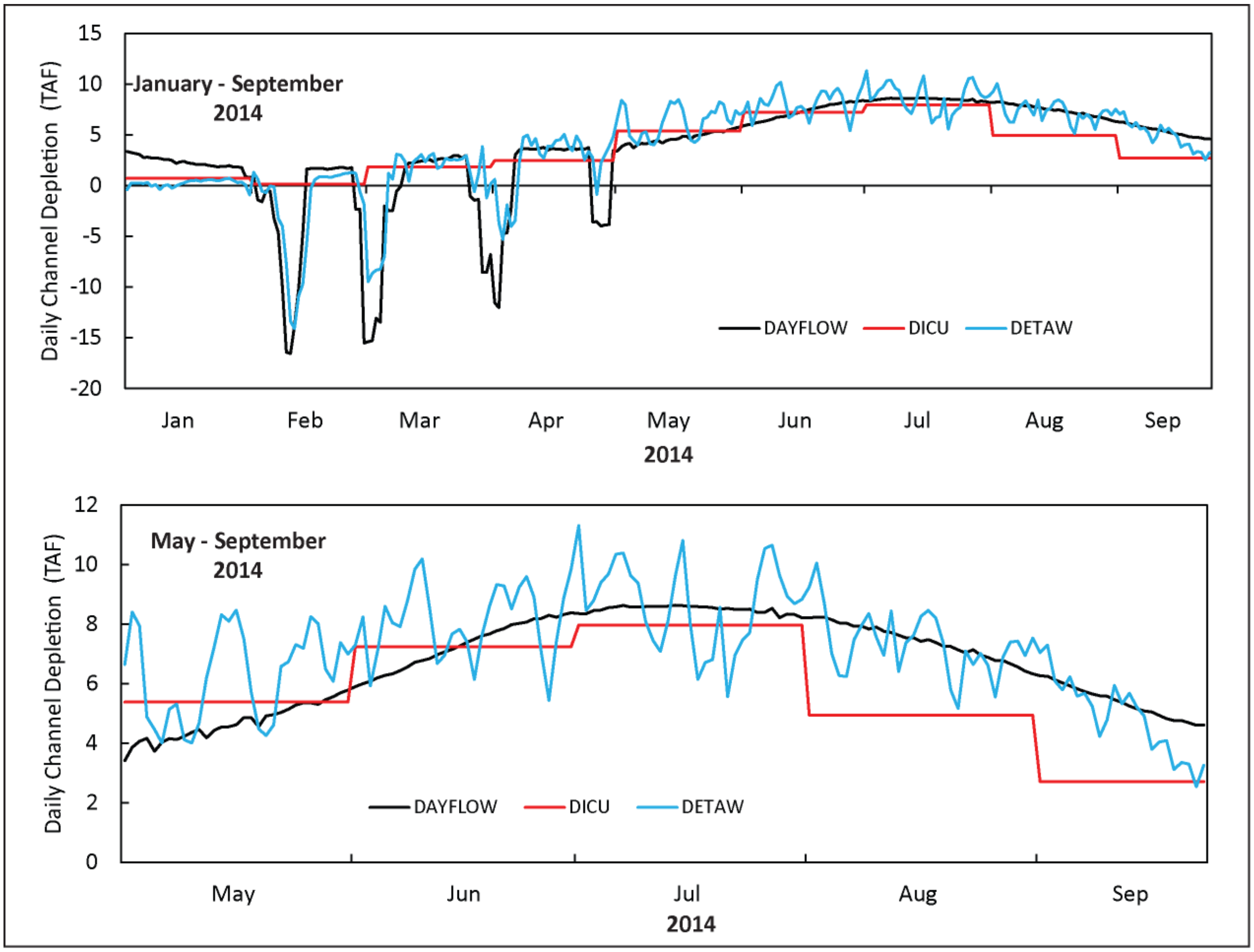


Figure 19: Sample Comparison of Daily Delta Channel Depletion for DAYFLOW, DICU, and DETAW

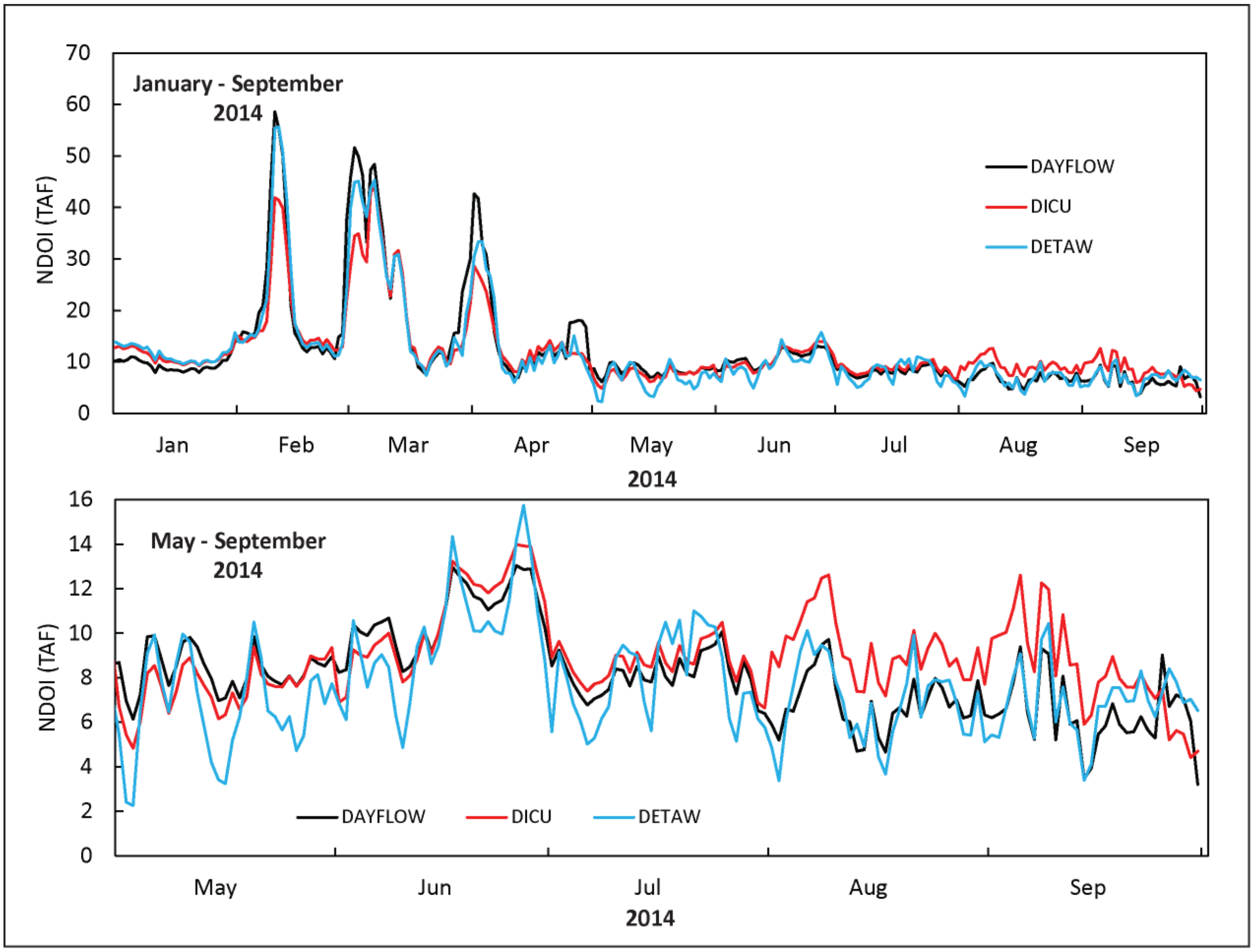


Figure 20: Sample Comparison of Daily Delta Outflow Index for DAYFLOW, DICU, and DETAW

2.7 Land use Data

As indicated in the previous sections, land use information is essential in the estimate of agricultural water demand. The distribution of croplands shows great variability across years due to crop rotation and market factors. In 2015 croplands in Central Valley are projected to be subject to unprecedented changes as a result of the impact of sequential dry years on the current conditions of the highly developed agricultural system. All these facts call for precise and timely land use projections to facilitate near-real-time model simulations. Unfortunately, at present there is no land use data directly available for this purpose. This section describes the procedure of collecting land use-related information from various sources and developing 2015 land use projections for demand estimates and model simulations.

As an input to CalSimHydro, land use data in 2015 have the same structure as the historical land use time series currently used by DWR in simulation models. The acreage of 23 agricultural and non-agricultural land use categories is summarized for each demand unit. Irrigated agricultural categories include alfalfa, almonds-pistachios, beans, corn, cotton, cucurbits, grain, onions & garlic, other deciduous, other field, other truck, pasture, potatoes, rice, safflower, sub-tropical, sugar beets, tomatoes (hand-picked), tomatoes (machine-picked), and vineyards. Non-agricultural categories are native vegetation, seasonal & permanent wetlands, and urban, for which there is no water demand for irrigation purpose. It is assumed that the acreage of seasonal & permanent wetlands and urban remains at the existing level of development in year 2015. Native vegetation refers to all vegetated areas that are not irrigated and managed, and this category is treated as the residue after finishing calculating the acreage of all other categories. Therefore, the development of 2015 land use focuses on irrigated agricultural land use categories.

The USDA Cropland Data Layer (CDL) in year 2014 was used as the basis of the 2015 land use projection. The CDL is a raster, geo-referenced, crop-specific land cover map created annually for the continental United States using moderate resolution satellite imagery and extensive agricultural ground truthing. All historical CDL products are available for use and free for download through the web portal by USDA. The release date of CDL is usually in the beginning of the next calendar year. The 2014 CDL at 30m resolution was released on Feb 2nd, 2015. For each spatial modeling unit, individual crop types were aggregated into the land use categories of CalSimHydro using a look-up table (Table 1).

Table 1. Specific crop classes in CDL and their corresponding land use category for the model of this study.

Value	CDL Class	First Crop Category	Second Crop Category
1	Corn	Corn	
2	Cotton	Cotton	
3	Rice	Rice	
4	Sorghum	Other Field	
5	Soybeans	Other Field	
6	Sunflower	Other Field	
10	Peanuts	Other Truck	
11	Tobacco	Other Truck	
12	Sweet Corn	Other Truck	
13	Pop or Orn Corn	Other Truck	
14	Mint	Other Truck	
21	Barley	Grain	
22	Durum Wheat	Grain	

23	Spring Wheat	Grain
24	Winter Wheat	Grain
25	Other Small Grains	Grain
26	Dbl Crop WinWht/Soybeans	Grain
27	Rye	Grain
28	Oats	Grain
29	Millet	Grain
30	Speltz	Grain
31	Canola	Other Field
32	Flaxseed	Other Field
33	Safflower	Safflower
34	Rape Seed	Other Field
35	Mustard	Other Field
36	Alfalfa	Alfalfa
37	Other Hay/Non Alfalfa	Pasture
38	Camelina	Other Field
39	Buckwheat	Grain
41	Sugarbeets	Sugar Beets
42	Dry Beans	Beans
43	Potatoes	Potatoes
44	Other Crops	Other Truck
46	Sweet Potatoes	Potatoes
47	Misc Vegs & Fruits	Other Truck
48	Watermelons	Other Truck
49	Onions	Onions and Garlic
50	Cucumbers	Cucurbits
51	Chick Peas	Other Truck
52	Lentils	Other Truck
53	Peas	Other Truck
54	Tomatoes	Tomatoes
55	Caneberries	Other Truck
56	Hops	Other Truck
57	Herbs	Other Truck
58	Clover/Wildflowers	Pasture
59	Sod/Grass Seed	Pasture
60	Switchgrass	Pasture
61	Fallow/Idle Cropland	Native Vegetation
62	Pasture/Grass	Pasture
63	Forest	Native Vegetation
64	Shrubland	Native Vegetation
65	Barren	Native Vegetation
66	Cherries	Other Deciduous
67	Peaches	Other Deciduous

68	Apples	Other Deciduous
69	Grapes	Vineyards
70	Christmas Trees	Other Deciduous
71	Other Tree Crops	Other Deciduous
72	Citrus	Sub-Tropical
74	Pecans	Other Deciduous
75	Almonds	Almonds-Pistachios
76	Walnuts	Other Deciduous
77	Pears	Other Deciduous
82	Developed	Urban
83	Water	Native Vegetation
87	Wetlands	Seasonal and Permanent Wetlands
92	Aquaculture	Native Vegetation
111	Open Water	Native Vegetation
112	Perennial Ice/Snow	Native Vegetation
121	Developed/Open Space	Urban
122	Developed/Low Intensity	Urban
123	Developed/Med Intensity	Urban
124	Developed/High Intensity	Urban
131	Barren	Native Vegetation
141	Deciduous Forest	Native Vegetation
142	Evergreen Forest	Native Vegetation
143	Mixed Forest	Native Vegetation
152	Shrubland	Native Vegetation
171	Grassland Herbaceous	Native Vegetation
176		Native Vegetation
181	Pasture/Hay	Pasture
190	Woody Wetlands	Seasonal and Permanent Wetlands
195	Herbaceous Wetlands	Seasonal and Permanent Wetlands
204	Pistachios	Almonds-Pistachios
205	Triticale	Grain
206	Carrots	Other Truck
207	Asparagus	Other Truck
208	Garlic	Onions and Garlic
209	Cantaloupes	Cucurbits
210	Prunes	Other Deciduous
211	Olives	Sub-Tropical
212	Oranges	Sub-Tropical
213	Honeydew Melons	Cucurbits
214	Broccoli	Other Truck
216	Peppers	Other Truck
217	Pomegranates	Other Deciduous
218	Nectarines	Other Deciduous

219	Greens	Other Truck	
220	Plums	Other Deciduous	
221	Strawberries	Other Truck	
222	Squash	Cucurbits	
223	Apricots	Other Deciduous	
224	Vetch	Pasture	
225	Dbl Crop WinWht/Corn	Grain	Corn
226	Dbl Crop Oats/Corn	Grain	Corn
227	Lettuce	Other Truck	
229	Pumpkins	Cucurbits	
230	Dbl Crop Lettuce/Durum Wht	Other Truck	Grain
231	Dbl Crop Lettuce/Cantaloupe	Other Truck	Cucurbits
232	Dbl Crop Lettuce/Cotton	Other Truck	Cotton
233	Dbl Crop Lettuce/Barley	Other Truck	Grain
234	Dbl Crop Durum Wht/Sorghum	Grain	Other Field
235	Dbl Crop Barley/Sorghum	Grain	Other Field
236	Dbl Crop WinWht/Sorghum	Grain	Other Field
237	Dbl Crop Barley/Corn	Grain	Corn
238	Dbl Crop WinWht/Cotton	Grain	Cotton
239	Dbl Crop Soybeans/Cotton	Other Field	Cotton
240	Dbl Crop Soybeans/Oats	Other Field	Grain
241	Dbl Crop Corn/Soybeans	Corn	Other Field
242	Blueberries	Other Truck	
243	Cabbage	Other Truck	
244	Cauliflower	Other Truck	
245	Celery	Other Truck	
246	Radishes	Other Truck	
247	Turnips	Other Truck	
248	Eggplants	Other Truck	
249	Gourds	Other Truck	
250	Cranberries	Other Truck	
254	Dbl Crop Barley/Soybeans	Grain	Other Field

Projected changes in 2015 land use were estimated by comparing crop acreage statistics by USDA between 2014 and 2015. Every year USDA conducts survey on agricultural production and releases crop statistics for the state of California following a fixed schedule. The total acreage of a specific crop type in the state was used as the main reference to quantify the land use change. Although statistical data might be available at a finer spatial resolution (for example, at county level), such a data set is usually not as timely available as the state total or the survey sample may not represent the full population. Table 2 shows the projected crop acreage change in 2015 compared to 2014. For example, according to data released on May 4th, 2015, almond acreage in 2015 is 102.3% as 2014. After the release date, the 2.3% increase was distributed evenly to all sub-areas in the Sacramento Valley. Prior to the release date, 2014 land use data from CDL was used because land use data in 2015 were unavailable. Walnut acreage was not released in 2015, and the change rate was calculated by assuming a linear trend from 2011 to 2014 based on the observation of historical acreage records.

Other crop types were assumed to remain at the 2014 land use level because of the lack of latest statistical data or other reasons. For example, grape (vineyard) is mostly grown in the San Joaquin Valley and coastal areas, and so the state total acreage may not reflect the land use distribution in the Sacramento Valley. If new statistical data sources or new methods of updating land use are discovered in the future, the land use change of these crop types will also be projected. At present, the same-year update is only conducted for the most important crop types, and the timeline of the update is shown in Table 3. The timeline is a reference when updating land use data for early projection in future years.

Rice is the most common crop and the largest water user in the Sacramento Valley. It is essential to improve the precision of water demand estimate for rice. Due to the high total water consumption by rice fields, the assumption of homogeneous land use change (as for other crops) may result in considerable error for rice. Therefore, a remote sensing based mapping approach was developed to obtain the spatial distribution of rice fields in the current year. The approach utilizes 30 meter resolution Landsat 8 images to capture the unique seasonal water signal of rice fields around the initial flooding stage, and creates a map of identified rice fields when rice seedlings just start growing. In 2015, the map was finalized in mid-June. Prior to the completion date of the remote sensing based map, the state total acreage by USDA was still used to project the percentage change of rice fields because of the lack of spatial distribution information before the growing season.

Table 2. Projected changes in crop acreage from year 2014 to 2015.

Crop	Acreage	Rate	Date	Source
Alfalfa	820000	93.7%	07/07/2015	USDA Pacific Region Results of Mid-Year Surveys
Almond	890000	102.3%	05/04/2015	USDA California Almond Acreage Report
Corn	430000	83.0%	03/31/2015	USDA Pacific Region Farm News
Safflower	59000	112.4%	07/07/2015	USDA Pacific Region Results of Mid-Year Surveys
Walnut		102.6%		Trend Analysis 2011-2014

Table 3. Dates of updating land use data and the corresponding data sources.

Date of Update	Crop	Source
Late Jan – Early Feb	All	USDA map (Cropland Data Layer) of previous year
Late Mar	Rice, Corn	USDA Pacific Region Farm News
Late Apr – Early May	Almond	USDA California Almond Acreage Report
Late May	Almond	USDA Pacific Region Farm News
Late May	Walnut	USDA California Walnut Acreage Report of previous year
Mid Jun	Rice	Map from automated method based on Landsat imagery
Late Jun – Early Jul	Rice, Corn, Alfalfa, Hay	USDA Pacific Region Results of Mid-Year Surveys
Early Jul	Almond	USDA Pacific Region Farm News
Early Aug	Rice, Corn	USDA Pacific Region Farm News
Early Sep	Rice, Corn	USDA Pacific Region Farm News

Table 4 and Table 5 show the projected 2015 land use acreage after updating all land use types for Delta and Sacramento Valley, respectively. To calculate water consumption in Delta, the acreage of 15 categories for Delta lowlands and uplands was used. For the Sacramento Valley, demand was estimated by CalSimHydro, which takes acreage of 23 categories for each Demand Unit (DU) as the land use input. In Table 5 the land use of 145 DUs was aggregated into 30 Water Budge Areas (WBA) to show the general spatial distribution.

Table 4. Projected 2015 acreage of land use categories in Delta.

	alfalfa	field	grain	native riparian	native veg	non-irrigated grain	orchard	pasture	rice	sugar beets	tomatoes	truck	urban	vineyard	water	Total
Lowlands	85,412	71,663	18,466	3	72,148	20,893	16,485	20,861	2,320	0	37,332	5,195	32,442	34,887	52,389	470,497
Uplands	23,986	6,978	10,471	1	54,114	5,413	13,171	22,960	3,036	0	9,539	2,929	45,241	7,742	3,856	209,436
Total	109,398	78,640	28,937	4	126,262	26,306	29,656	43,820	5,356	0	46,871	8,124	77,682	42,630	56,244	679,932

Table 5. Projected 2015 acreage of land use categories for all Water Budget Areas (WBA) in the Sacramento Valley. Hand-picked and machine-picked tomatoes are not distinguished.

WBA	Alfalfa	Almonds-Pistachios	Beans	Corn	Cotton	Cucurbits	Grain	Onions and Garlic	Other Deciduous	Other Field	Other Truck	Pasture	Potatoes	Rice	Safflower	Sub-Tropical	Sugar Beets	Tomatoes	Vineyards	Native Vegetation	Seasonal and Permanent Wetlands	Urban	Total
02	254	20	3	9	0	0	46	0	511	10	2	4,502	0	1	0	320	0	4	17	178,815	0	42,357	226,871
03	31	10	4	1	0	0	77	0	217	4	2	1,478	0	2	0	143	0	0	4	155,891	0	51,758	209,623
04	3,745	8,147	94	1,014	11	1	2,112	1	9,973	188	138	3,710	89	175	31	4,415	0	7	96	412,539	0	22,412	468,898
05	534	16,811	16	165	20	1	878	1	28,499	155	328	1,974	1	110	3	2,190	0	127	75	125,815	296	6,723	184,721
06	4,119	3,930	12	334	3	0	903	0	1,582	16	111	148	0	19	1	1,242	0	5	18	20,705	0	4,674	37,822
07N	9,520	40,763	399	4,906	1,438	12	12,535	7	12,278	1,876	646	573	0	1,109	794	6,517	1	645	47	186,800	0	5,266	286,131
07S	8,451	62,565	881	275	27	367	11,162	85	6,596	7,091	836	1,989	0	894	459	667	0	15,137	2,387	267,603	0	4,549	392,023
08N	2,840	8,737	341	1,033	79	33	1,981	32	16,940	971	238	408	0	78,295	266	211	0	563	41	44,958	15,326	3,841	177,137
08S	7,930	7,974	3,087	1,553	18	1,198	9,464	21	10,730	9,944	638	1,175	0	76,128	2,167	50	27	13,969	180	75,449	10,955	5,100	237,757
09	1,956	5,199	1,699	3,211	269	211	4,490	17	20,477	2,333	183	397	0	16,668	48	101	0	610	9	33,247	8,396	512	100,031
10	365	23,313	110	51	19	2	705	0	7,830	144	13	232	0	6,652	5	1,900	0	7	22	68,141	671	20,550	130,732
11	3,493	4,438	203	365	11	1	831	1	29,479	1,251	421	587	0	99,495	91	295	0	447	15	97,966	7,614	10,156	257,159
12	332	657	17	13	0	3	622	0	5,202	16	4	505	0	1,706	2	105	0	4	2	22,310	777	4,657	36,933
13	440	300	1	4	0	0	143	0	183	1	0	278	0	0	0	74	0	1	2	67,717	0	6,974	76,118
14	170	185	2	7	0	0	22	0	521	1	88	137	0	2,048	1	53	0	1	2	62,321	0	6,073	71,632
15N	383	938	17	25	0	0	370	0	12,304	23	385	166	0	13,898	2	87	0	7	5	18,848	0	3,789	51,248
15S	2,297	2,104	59	652	0	21	1,762	1	13,049	182	4	3,214	0	14,204	14	84	0	77	205	57,627	0	10,429	105,986
16	1,740	3,054	376	62	1	15	1,107	1	22,883	817	16	245	0	2,108	112	259	0	820	329	20,054	0	10,536	64,536
17N	313	4,526	34	8	0	0	235	1	1,480	109	22	98	0	2,080	13	354	0	62	13	24,310	13,639	207	47,505
17S	804	1,694	1,668	220	87	12	743	2	1,968	526	17	312	0	2,196	106	110	0	1,061	29	30,272	2,019	1,773	45,622
18	233	259	2,147	531	288	10	3,473	1	4,186	2,696	632	128	0	6,696	784	11	0	2,669	3	9,651	0	397	34,795
19	1,051	185	1,910	1,878	0	341	3,535	1	3,163	7,962	102	214	0	19,884	368	8	0	8,581	86	17,381	0	568	67,218
20	23,739	16,071	1,183	974	2	68	22,564	427	10,411	9,518	431	8,392	0	108	2,405	1,480	2	17,800	3,545	169,916	0	24,479	313,515
21	3,557	749	322	310	0	708	2,845	81	3,135	2,293	49	1,110	0	4,997	956	12	0	4,557	176	27,239	500	2,124	55,719
22	3,862	226	134	371	0	150	3,920	55	2,676	800	89	4,114	0	19,319	189	22	0	575	193	18,445	0	5,418	60,561
23	1,932	792	275	237	0	5	1,647	2	7,162	99	4	2,967	0	24,396	14	20	0	81	111	34,963	0	2,182	76,888
24	1,502	210	49	151	1	7	2,018	0	441	48	7	5,517	0	4,803	2	21	0	29	42	148,329	0	22,579	185,757
25	24,722	7,984	845	2,646	1	149	21,601	61	8,373	10,892	553	18,980	0	340	1,156	263	0	11,435	1,065	130,233	0	19,261	260,560
26N	495	248	1	7	0	0	679	3	411	21	2	1,649	0	296	11	9	0	2	157	26,733	0	108,824	139,549
26S	3,857	210	24	1,071	0	203	2,054	1	326	65	7	11,650	0	0	37	14	0	107	2,472	62,865	0	88,155	173,121
Total	114,671	222,297	15,914	22,086	2,276	3,520	114,526	804	242,986	60,050	5,970	76,850	91	398,628	10,040	21,038	30	79,390	11,347	2,617,141	60,193	496,323	4,576,169

3 Direct measurement of Net Flow

3.1 Background

The difficulties of directly observing net flow on big channels are severe and we believe this message has been communicated well by the agencies (USGS and DWR) that perform the monitoring. Rio Vista and Jersey Point regularly experience tidal fluctuations of over 150,000cfs. Quantifying outflow requires extracting a net flow component as low as 2,000cfs from that tidal signal at each station. This has been referred to as a "signal-to-noise" problem by the USGS Delta Hydrodynamics Group. The noise in this case is not really the tidal flow but systematic errors that might share its scale -- even a 2% glitch concentrated in one limb of the tide cycle could average out to a 100% error in net flow.

Furthermore there are ways in which the flow station calibration process specifically favors tidal frequencies at the expense of subtidal, a point we believe has received little recognition. Establishing a flow station in the Delta usually involves two steps. First, a permanent sideways-looking instrument is deployed on a pile or other fixture and sends a beam out over part of the channel. A representative portion of the beam is averaged to produce an "index velocity". To convert this index velocity to a flow, it must first be related to a cross-sectional average velocity using a rating equation (typically linear or regression) and finally the average velocity is multiplied by an area to obtain flow. Calibration data for the rating comes from independent collections in boats using downward-directed ADCPs. Each collection involves numerous crossings of the entire channel over a 12-25 hour session, a length of time which covers one period of the main tidal components. This fitting gets augmented over the years under different hydrologic conditions, and any important station eventually accumulates a database of perhaps a half dozen full length outings and numerous shorter cross-checks before equipment gets swapped or repositioned and the process starts anew.

Consider now how such a sampling and fitting process treats the signal at subtidal frequencies, which have periods of 5-30 days or longer for seasonal hydrology. At these longer time scales, a calibration session of 25 hours represents effectively a single moment and cannot be distinguished from the station mean. Collecting 5-10 sessions scattered over the years does little to help. Even if we had samples spanning longer undulations, there is no place in the standard rating formula to incorporate them. The rating regression includes no notion of frequency: it can be likened to an audio system with only a volume knob, not separate treble and bass.

While some problems of net flow measurement have been understood for quite some time, they have traditionally been hard to quantify. The DWR and USGS regularly spot check instantaneous flow, at least on wind-free days, and often the checked values have an accuracy of 5-10%. However, these are just point values. There is no easy translation from error in instantaneous tidal flow to error in net flow.

One way to visualize the errors in this band (and a key to ultimately compensating for them) is to look at discrepancies in mass balance between the outflow locations and neighboring stations. In 2015, DWR added two stations at the downstream end of Steamboat Slough (SXS) and the Sacramento above Steamboat (SIO) shown in pink in Figure 1. Together with existing stations RYI and SVR, these sites form a very small region or "control volume" above the Rio Vista station. Because of its small area, this control volume will receive minimal consumptive use or storage change – we estimate that a simple sum of the inflows and outflows should sum to a maximum of 100-200cfs (often much less) on a tidal net basis. We will refer to a sensible mass balance as "closure".

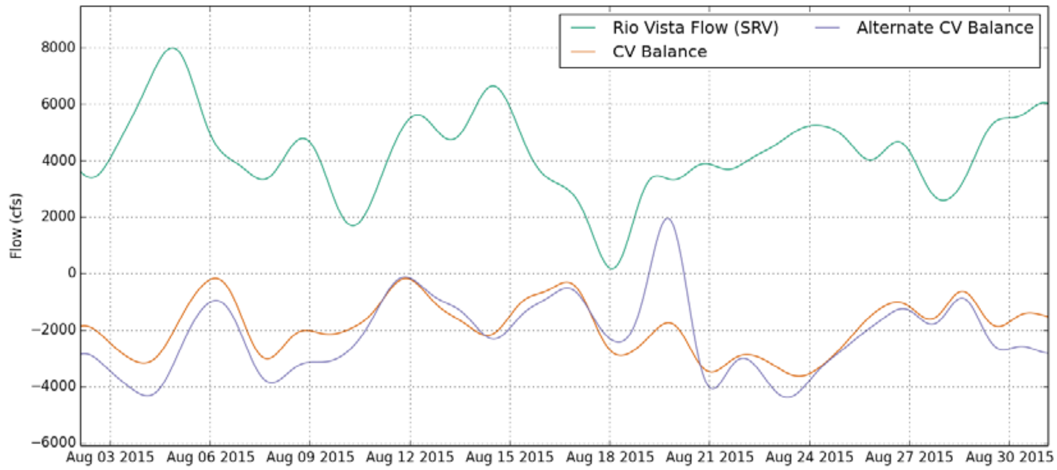


Figure 21: Closure in a control volume around the Rio Vista (SRV) station. The green line is flow at Rio Vista. The other two are the closure imbalances for control volumes involving two different choices of upstream stations. The red line is the one associated wi

In fact, the control volume stations do not sum to anything like zero or 200cfs, but rather to negative thousands (extra flow out). Figure 21 shows the 2015 sum of flows into the small control volume and compares it to the flow at Rio Vista. We have tested not only this control volume but similar ones involving other permutations of upstream stations and conclude that for any control volume containing Ryer Island (RYI) and Rio Vista (SRV), closure error for much of the 2015 summer season was -1,500cfs to -2,000cfs, or half of a typical Rio Vista subtidal flow. The shape of the error in time is important as well -- it looks like a mirror image of flow. Given that Rio Vista is an outflow and contributes negatively to closure error under our sign conventions, the plot is indicating that the station rating is over-amplifying this band of the signal. The highs should be lower and the lows should be higher
Little about long term performance at Rio Vista can be gleaned just from this plot. First, there is no conclusive way to tease apart the contributions of Cache Slough and Rio Vista. Second, even if we were willing to attribute most of the discrepancy to Rio Vista, the error is highly nonstationary over time. In 2015, Rio Vista gage overestimates outflow. However in 2013, a time when NDO versus NDOI came under some scrutiny, the reverse was true. Based on flow balances with nearby stations available at the time, Rio Vista was under-estimating outflow on a sustained basis by 1000-2000cfs.

Low frequency errors at the other three stations (Threemile, Dutch Slough and Jersey Point) are harder to pin down because their geographical layout makes them harder to incorporate in simple control volumes. Whereas the Sacramento River neatly branches into narrower channels immediately upstream, which are typically more accurate, the San Joaquin stays wide and is more intricately connected to other channels in the Delta. The three stations have to be lumped together in a control volume that includes quite a few additional upstream stations to achieve a closed system, and accounting for storage change is more difficult. Nevertheless, we have done this analysis as part of the multiple control volume project described in section 3.2 and the results suggest outflow was shorted 3000-3500 cfs in 2013 by these three stations in addition to a sustained shortfall of 1000-1500cfs by Rio Vista.

3.2 Multiple Control Volumes: Expanding Direct Measurement

The Multiple Control Volume (MCV) method of outflow estimation attempts to reduce the uncertainty of direct measurement described in section 1 by bringing more measurements into the effort and incorporating regions with less disadvantageo*u*s signal-to-noise ratios. Instead of using just the four designated NDO outflow stations to measure outflow, MCV includes dozens of stations and every possible flow balance in the Delta simultaneously. The approach looks spatial or like a model, but the end goal is not to create a collage of low-accuracy regional estimates but rather to gather statistical strength concerning summary quantities like NDO.

The starting point for the MCV approach is a map such as the one in Figure 22. The Delta is split up into twenty or so patches (more are available now than in 2014 when our project began), which are connected with one another at flow monitoring sites. At the outer boundary of the system, flows are assumed to be monitored either as flow stations or as exports.

Within every control volume, we assume a mass balance at subtidal time scales: change in storage is the result of inflows, outflows and channel depletions. The mass balance would be exact based on exact flows, but these are not known but rather measured with considerable error. Figure 23 shows the flow balance at a control volume in the South Delta (E11 on the map in Figure 22). The sum of observed flows into the volume in blue is not zero, but matches the expected local net channel depletions shown in green pretty well. Figure 24 shows the flow balance at the Delta Cross Channel which superficially shares a similar seasonal pattern. However, on closer inspection, the volume is far too small to support much storage change or local net channel depletions and the mismatch is caused almost entirely by flow errors. The magnitude of flow balance errors is greatest close to the western boundary, as we showed for Rio Vista in section 1] in the context of a very small control volume. Figure 25 shows the control volume containing Jersey Point, Threemile and Dutch Sloughs (E6 is the union of E6a and E6b). The sums of flows into the volume are out of balance by many thousands of cubic feet per second with step changes of 8,000cfs and apparent exaggerated seasonality.

To distinguish the local net channel depletions from flow errors we have to factor in several algebraic constraints and insights about the nature of the flows and errors, important examples of which are these:

1. The “true” flows balance.
2. Any net flow error that adds positive mass discrepancy in one control volume will introduce an exactly matching negative mass discrepancy in the connected neighbor.
3. Flow errors are mostly stationary, centered fairly near zero, but with long drifts and stochastic cyclical components at typical subtidal frequencies.
4. Except for Freeport, boundary flows and exports do not have any cyclical components.
5. Subtidal errors at flow station are mutually independent between stations but auto correlated (this is the least credible assumption and one that is currently being relaxed).
6. Local net channel depletions are driven at least partly by common patterns that are shared between control volumes. We use either a common factor model or gently modulate an existing physical-conceptual model (DICU, DETAW) in space or time.

Of particular value is the contrast between assumptions (2) and (6). Discrepancies that rob from one patch to give to another tend to be labeled as flow errors, whereas inflow-outflow discrepancies that are similar between patches tend to be associated with local net channel depletions.

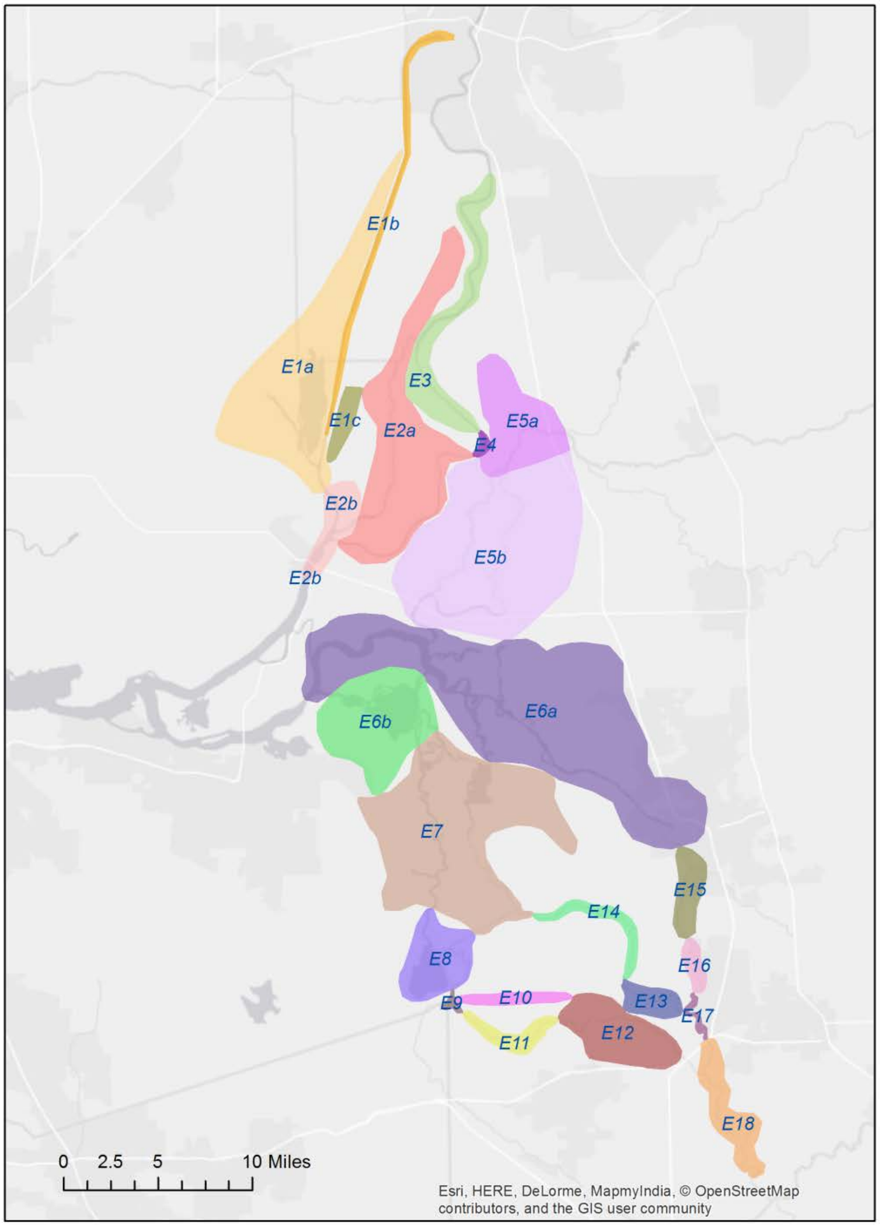


Figure 22: Control volumes available as of 2015.

The computational vehicle for the MCV method is a 20-30 patch linear state space model along with estimation using a Gibbs sampler, which is a Bayesian statistical technique well suited to this large model built from routine parts. The observations in the model are the flow closures from each patch, constructed from observation errors, local net channel depletions and volume change. The state variables include flow errors and local net channel depletion components.

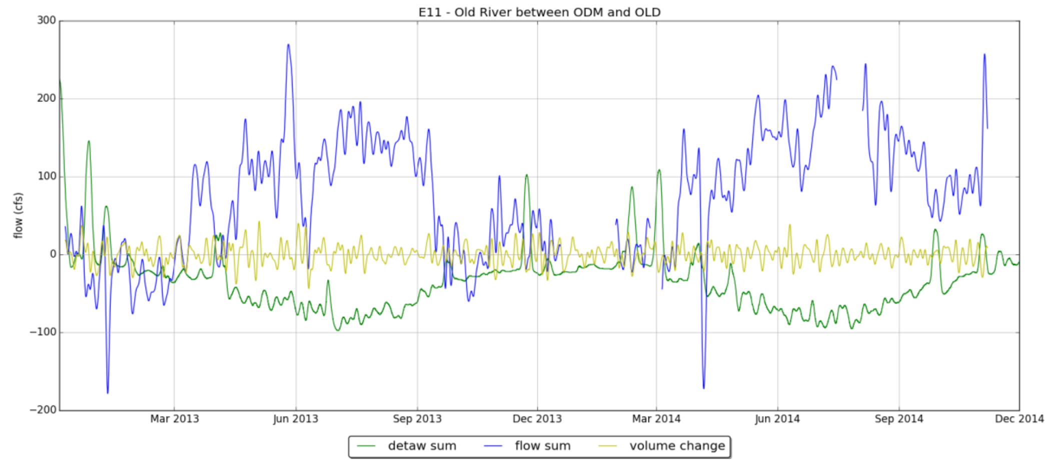


Figure 23: Mass balance in a reach of Old River.

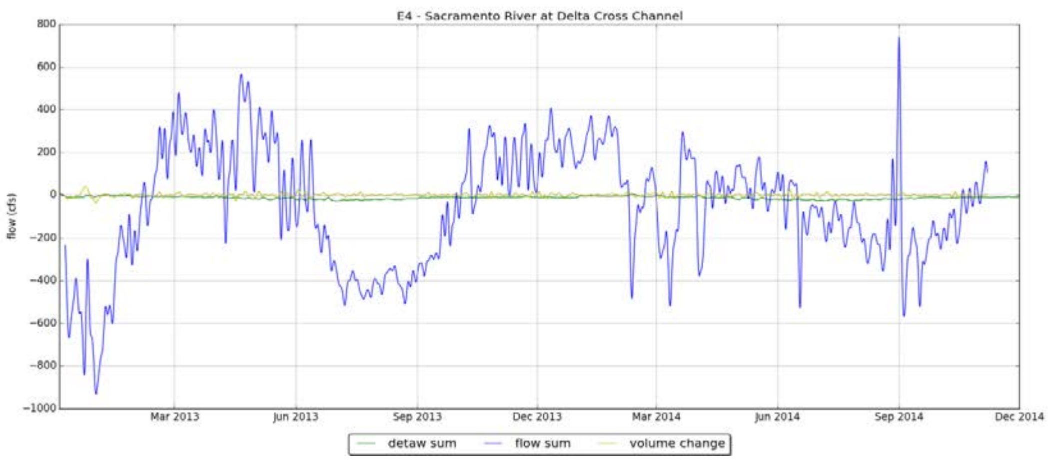


Figure 24: Mass balance around Delta Cross Channel.

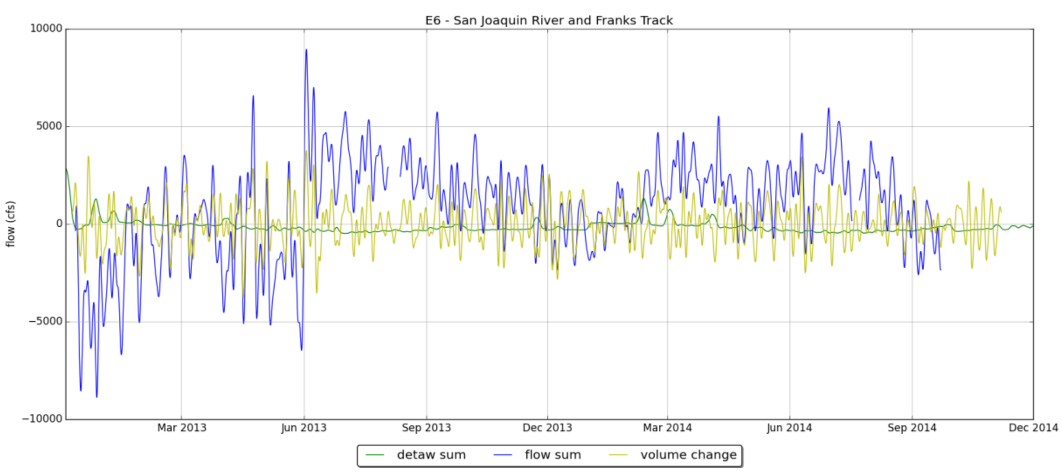


Figure 25: Mass balance above Jersey Point.

The technical details will be addressed in a forthcoming annual report[1] chapter for the Delta Modeling Section. At the moment we are able to produce plausible flow corrections that tally well with mass conservation. We are currently using bootstrapping and simulation-based statistical techniques to show the model is estimable with reasonable uncertainty with some degree of model misspecification.

This is a data intensive method and one question we commonly get is how much needs to be invested to make this system work well. We can complete some proof of concept without additional investment. However, additional stations would help bolster monitoring in locations that are either difficult have a distinctive local net channel depletion character (such as the East Delta or upper Cache Slough). Some areas with the largest local net channel depletions enjoy surprisingly little monitoring currently. Assuming resources are available, proposed additions are listed below, batched in groups that would have to be installed together to create closed systems:

1. Sacramento I Street (needs ADCP for low flow)
2. Threemile Slough (redundant station, hopefully near the Sacramento River).
3. Potato Slough (shrinks some of the large control volumes on the East Side)
4. Little Connection, Disappointment and 14-mile Slough (3 is a prerequisite).
5. Cache Slough
6. Lindsay Slough

The ongoing cost for all of these monitoring additions is generally estimated to be $0.5M.

[1] Methodology for Flow and Salinity Estimates in the Sacramento-San Joaquin Delta and Suisun Marsh, Annual Progress Report to the State Water Resources Control Board in Accordance with Water Right Decisions 1485 and 1641.

4 Salinity Inversion

4.1 Outline of approach

The effects of the net flow are well known and documented to be the primary driver for salinity in the Delta. Over the years, there has been much improvement in our understanding and modeling of the relationship between flow and salinity. The models range from X2 auto-regressions based on power laws from early estuarine circulation models (Kimmerer, 1992) to G-model derivatives based on steady state advection-dispersion and the idea of antecedent outflow (Denton, 1993). Following more of a machine learning approach, Artificial Neural Networks are currently used for estimating water costs in planning simulations (California Department of Water Resources, 2001). Finally, hydrodynamic and transport models such as DSM2, RMA, UnTRIM and SCHISM are routinely applied in the Delta for the purpose of understanding the flow salinity relationship in ever-increasing detail.

A core idea of this approach is to use flow-salinity relationships to verify estimates of outflow by examining how well they tally with observed salinity. This is often done visually by providing the inputs of NDOI to forward models, simulating salinity at various locations in the Delta and comparing the results to field data. The idea can be formalized in a Bayesian framework, provided that the calibration or training of the forward model adequately spans the variation in the data.

The approach can be taken one step further and used to invert salinity to estimate NDO. An example is given below. There are a couple of barriers to applying this approach. One is that the inverse problem tends towards being ill-posed -- there are potentially many flows that could fit salinity almost equally well. This can be addressed by further constraining the solution with smoothness requirements or other regularization or by treating the standard NDOI as a prior to be refined. Another barrier is that inverse techniques typically involve many simulations, so that they are most tractable with empirical models and very fast simulations.

4.2 Example using PEST and Martinez Salinity Generator

The original G-Model related salinity intrusion (and X2) in the western Delta to outflow. The model was later changed to add the effect of Delta filling and draining on flow, and the DWR added a method to disaggregate the output salinity tidally and use the model to estimate salinity at Martinez using NDO (California Department of Water Resources, 2001). We call this method the Martinez Salinity Generator.

Using this empirical model with the Parameter Estimation (PEST) program and Martinez Historical EC for 2014 we have inverted salinity to obtain the result shown in Figure 26. The parameters estimated in this experiment were NDO daily values and the regularization was used to smooth the estimate, although other formulations remain under investigation. The output is closer to NDOI than to NDO – the method incorporates subtidal oscillations in its formulation, but as “net flow”.

Other salinity-flow relationships have been used for the same inverse problem. For instance, (Russ T. Brown and Anne Huber, 2015) used a similar approach to estimate NDO using X2 values. Other options would be to use DSM2 hydrodynamic transport models or Artificial Neural Networks. Similarly, while PEST allows inverse modeling with a variety of constraints and regularization terms, other tools include assumptions that are more specifically tuned for obtaining estimating unknown source terms in a dynamic model. These include inverse modeling techniques used in oceanography and atmospheric science: adjoint data assimilation or Bayesian filters. Our experience with salinity-based techniques is that they are powerful in identifying possible anomalies in traditional NDOI by highlighting where it appears to violate the historical salinity-outflow relationship, but that on their own these techniques are not definitive in settling some of the questions they create.

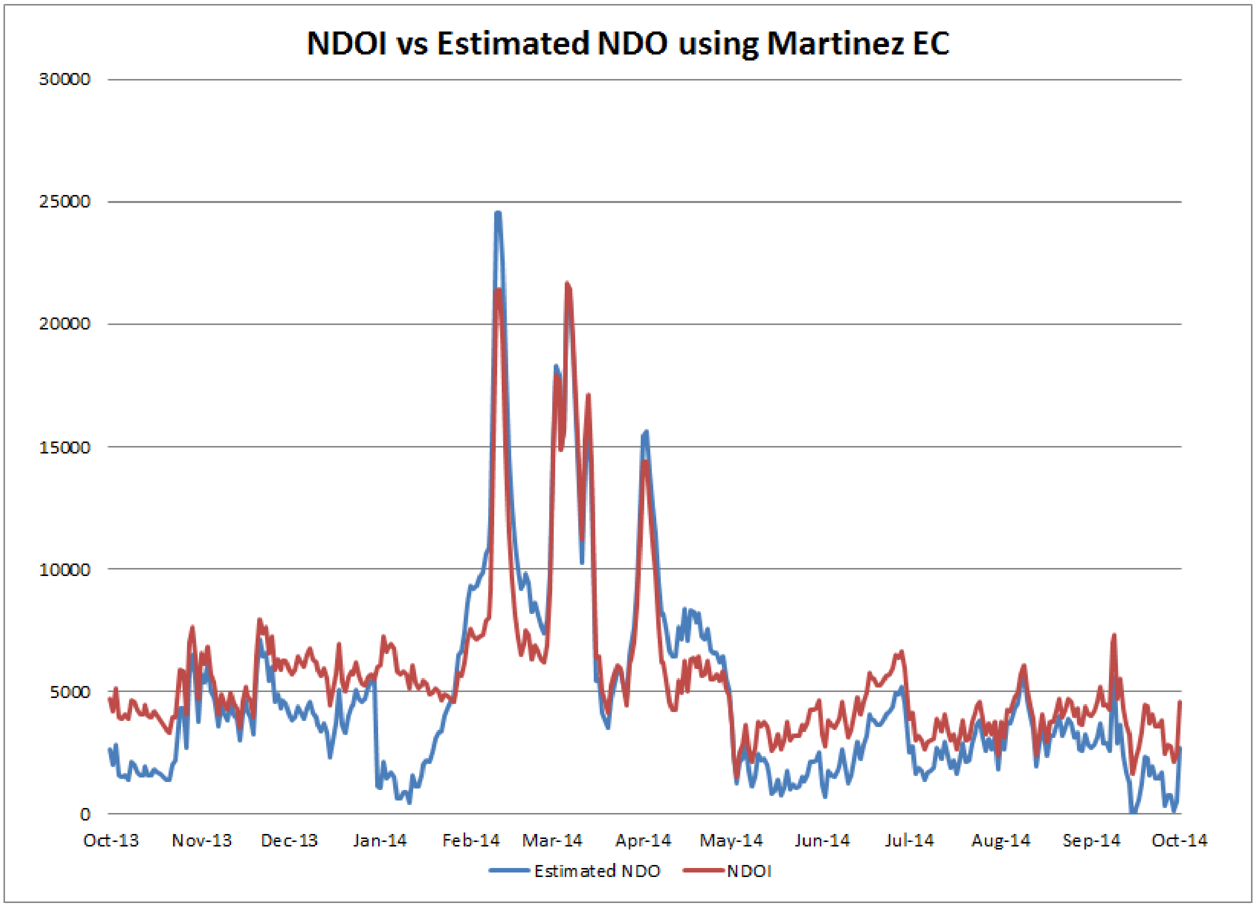


Figure 26: NDOI vs Estimated NDO using Martinez EC

5 Summary, Recent Activities and Possible Future Directions

5.1 Summary

In this report we have summarized work being done to improve the standard NDOI approach, particularly gross channel depletions. We have also described alternate approaches based on direct measurement and salinity inverse problems that have received serious attention in the past two years.

We believe an NDOI-like approach is still the best available science today and its product the most appropriate for regulatory purposes. If a variety of indexes is under consideration, the criteria for success and what is meant by “net” will have to be considered in more rigorous terms. We have described the difference between NDOI and observed NDO, with NDOI emphasizing only the undercurrent of flow resulting from upstream inputs and NDO mixing these with mid-system oscillations due to tidal filling and draining forced from the ocean side

The current state of the art is improving. The research and reporting described below will certainly improve our understanding of consumptive use.

5.2 Recent Activities and Possible Future Directions

5.2.1 Delta Water Master led investigations

In response to drought situation in California, the newly appointed Delta Watermaster with the SWRCB initiated a project early 2015 to estimate Delta consumptive use using different approaches for the growing season of 2015 (and to be extended to 2016 also). This project was kicked off with a large meeting setup by the Delta Watermaster and involved stakeholders across the water community (DWR, SWRCB, BOR, Delta water agencies, project contractors, UCD, consultants, local districts, etc.). The project is funded by the SWRCB, and the technical aspects are being coordinated by UCD. The project includes estimation of actual ET using ground instrumentation, remote sensing approaches, and computer modeling. Due to delays in getting the contract funded, securing agreements with Delta water agencies on instrumentation placements and maintenance, purchasing of instruments (e.g., CIMIS stations), etc. the data collected did not start until mid-June 2015 (on three islands). Meanwhile, DWR contracted with Land-IQ to carry out remote-sensing / ground truthing effort to estimate the crop and other land classification acreages in the Delta for 2015, for use in the simulation models of the Delta. The final product, which will be documented and peer reviewed, will include a comparison of several remote sensed approaches (in double blind experiments) to compute actual ET along with DWR’s DETAW model. Uncertainty of the estimates will also be addressed.

5.2.2 Groundwater

The Department is currently modeling efforts to better understand the interplay between seepage from channels and ground water and how they are used to meet consumptive demands. Understanding impacts of Groundwater on Consumptive Use and channel depletions is an important area of investigation but also an area of large uncerntainty requiring better understanding of farming practices, changing water table levels, and seepage throughout the different areas of the Delta.

5.2.3 Improved reporting

In the past two years, changes such as SB88 have raised hopes of improved reporting of agricultural water use. The volume of diverted water is a sub-prediction of both DICU and DETAW channel depletion models that currently cannot be independently corroborated. If accurate, better reporting of diversions will provide the numbers needed to do so.

As far as we know, the water quality of return flows has not been recently studied. The volume and water quality from island returns in the various stages of agriculture is of independent interest for understanding water quality in the Delta. A more subtle point is that mass fluxes of salt contain information concerning the water balance and NDO as well. The multi-control volume approach outlined in section 3 is easily augmented to consider closure differences in salt flux as well as water – the reason we do not include salt right now is that don't know observe either the volume or the concentration of returns, so salt introduces more unknowns than it does information.

5.2.4 Increased instrumentation for flow

In section 3, we described monitoring locations that could be set up expressly for the purposes of increasing our understanding of consumptive use. In some cases, these are meant to introduce redundancy in regions where subtidal flow monitoring is difficult. In others, it is meant to isolate regions with a strong or distinctive consumptive use signal and fewer observational problems.

6 Bibliography

California Department of Water Resources. (1956). *Report No. 2: Water Supply and Water Utilization on Medford Island.* DWR.

California Department of Water Resources. (1956). *Report No. 4: Quantity and Quality of Waters Applied to and from the Delta Lowlands.* DWR.

California Department of Water Resources. (1959). *Report No. 3: Water Supply and Water Utilization on McDonald Island.* DWR.

California Department of Water Resources. (1962). *Appendix to Bulletin No. 76: Salinity Incursion and Water Resources.* 1962: State of California.

California Department of Water Resources. (1965). *Sacramento-San Joaquin Delta Area Land Use Survey Data.* DWR.

California Department of Water Resources. (1994). *Background Report on Agriculture.* DWR.

California Department of Water Resources. (1995). *Estimation of Delta Island Diversions and Return Flows.* DWR.

California Department of Water Resources. (2001). *Methodology For Flow and Salinity Estimates in the Sacramento-San Joaquin Delta and Suisun Marsh.*

California Department of Water Resources. (2015). *Current Full Dayflow Documentation*. Retrieved November 2, 2015, from Dayflow: An Estimate of Daily Average Delta Outflow: http://www.water.ca.gov/dayflow/documentation/dayflowDoc.cfm#Introduction

California Department of Water Resources. (2015). *Dayflow Data*. Retrieved November 2, 2015, from Dayflow: An Estimate of Daily Average Delta Outflow: http://www.water.ca.gov/dayflow/output/

California Department of Water Resources. (2015). *Methodology for Flow and Salinity Estimates in the Sacramento-San Joaquin Delta and Suisun Marsh.* Sacramento: Department of Water Resources.

Davids Engineering, Inc. (2012). *Remote Sensing: Consumptive Use Analysis*. Retrieved November 2, 2015, from Davids Engineeting, Inc.: http://davidsengineering.com/projects/remote-sensing/california-department-water-resources-analysis/

Denton, R. a. (1993). *Antecedent Flow-Salinity Relations: Application to Delta Planning Models.*

Kadir, T. (2006). *Estimates for Consumptive Water Demands in the Delta using DETAW.* DWR.

Kimmerer, W. a. (1992). An estimate of the historical position of 2ppt salinity. *Managing freshwater discharge to the San Francisco*.

Liang, L., & Suits, B. (2015). *Annual Report, Chapter 3. Estimating the Impact of Groundwater on Delta Channel Depletions.* DWR.

Russ T. Brown and Anne Huber, I. I. (2015, Feburary 17). Relationships between Measured X2 and Equivalent Outflow (cfs) and. *DSM2 User Group Meeting*.