Chapter 8 User-Defined Linear Programming Constraints

The WEAP software determines the allocation of water at each time step using a form of linear programming (LP) known as Mixed Integer Linear Programming (MILP). The MILP problem consists of an objective function and a set of linear constraints. The objective function is defined in terms of priorities (weights) and associated decision variables (e.g., storage, streamflow, deliveries). The linear equations that constrain the values of the decision variables typically relate to system connectivity, physical capacities, and regulatory limits on diversions and storage (e.g., water rights, flood control requirements). WEAP is designed to automatically build the objective function and constraints from its built-in model objects (e.g., rivers, demand nodes, groundwater nodes), each of which are endowed with properties that act as constraints (e.g. reservoir storage capacity, maximum diversion capacity) and/or objectives (e.g. MFRs, water demand, water storage). However, for complex water resource systems additional constraints may be needed. This happens, most frequently, in cases where a decision variable is conditional upon another decision variable. For example, the flow over a weir is dependent on the upstream flow in the river.

User-defined variables may be “state” variables or “decision” variables. The value of state variables are known, or are calculated at the beginning of the time step, prior to solving the water allocation problem. The value of decision variables are determined by the MILP solver. Generally, state variables are defined in SacWAM under Other Assumptions.

User-defined variables have one of the following forms:

- DefineLPVariable: A standard LP decision variable (i.e., positive real number).
- DefineIntegerLPVariable(0,1): An integer decision variable that may have a value of zero or one.
- DefineLPVariable(-999999,999999): An LP decision variable with a lower bound of -999,999 and an upper bound of 999,999.

This chapter briefly describes the UDCs implemented in SacWAM. They are described in alphabetical order. Brief background information is presented for each UDC. The section headings correspond to branches in the WEAP data tree. This information supplements material presented in Chapter 7 and addresses many of the same aspects of the model.

8.1 Artificial Neural Network

Operation of CVP and SWP facilities is partially dictated by the need to meet D-1641 water quality objectives for the Delta. DWR has developed an ANN that mimics Delta flow-salinity relationships as simulated in the one-dimensional hydrodynamic and water quality model, DSM2 (Sandhu 1995, Wilbur and Munévar 2001). Inputs to the ANN include Delta inflows, San Joaquin River salinity, Delta Cross Channel (DXC) gate position, and Delta exports and diversions.\(^{19}\) Values for each of these parameters for

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\(^{19}\) The ANN also uses an indicator of tidal energy.
the previous five months are inputs to the ANN, representing an estimate of the length of memory of antecedent conditions in the Delta. The ANN also needs monthly Delta salinity standards and compliance locations.

DWR’s ANN is implemented in SacWAM to determine Delta outflow requirements for salinity control. The ANN does not explicitly compute a flow requirement that SacWAM tries to meet. Rather, it specifies a set of linear relationships between Delta exports and Sacramento River inflows that must be maintained to meet D-1641 Delta water quality standards at four compliance locations (Collinsville, Emmaton, Jersey Point, and Rock Slough). Additionally, the ANN provides salinity estimates for Clifton Court Forebay and Contra Costa WD Los Vaqueros diversion locations (Old River and Victoria Canal). The ANN may also be used to calculate Delta salinity at the various compliance locations for the preceding time step once all Delta flows have been determined.

8.1.1 ANN Input

Simulated data passed to the ANN include previous time step values of combined exports at Banks and Jones pumping plants, Contra Costa WD diversions, and Barker Slough Pumping Plant for the North Bay Aqueduct, Sacramento River flow at Hood, San Joaquin River flow at Vernalis, and Yolo Bypass flow at Lisbon Weir. User-defined decision variables are defined for these flow components to provide a shorthand method of referring to these flow components when calling the ANN. These user-defined decision variables are listed in Table 8-1.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Variable Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>D409</td>
<td>Decision variable</td>
<td>California Aqueduct and Delta-Mendota Canal combined exports</td>
</tr>
<tr>
<td>C400</td>
<td>Decision variable</td>
<td>Sacramento River at Hood (RM 041)</td>
</tr>
<tr>
<td>C157</td>
<td>Decision variable</td>
<td>Yolo Bypass at Lisbon Weir (below Putah Creek confluence)</td>
</tr>
<tr>
<td>C639</td>
<td>State variable</td>
<td>San Joaquin River at Vernalis</td>
</tr>
<tr>
<td>DXC</td>
<td>State variable</td>
<td>Fraction of month that Delta Cross Channel is open</td>
</tr>
<tr>
<td>DICU</td>
<td>State variable</td>
<td>Delta island consumptive use</td>
</tr>
<tr>
<td>Sac_oth_est</td>
<td>State variable</td>
<td>Delta inflow from Calaveras, Cosumnes, and Mokelumne rivers, Marsh Creek, and Yolo Bypass less diversions at Barker Slough Pumping Plant used for current time step</td>
</tr>
<tr>
<td>Sac_oth</td>
<td>State variable</td>
<td>Delta inflow from Calaveras, Cosumnes, and Mokelumne rivers, and Marsh Creek, less diversions at Barker Slough Pumping Plant used for previous time steps</td>
</tr>
<tr>
<td>Exp_oth</td>
<td>State variable</td>
<td>Delta diversions by Contra Costa WD and the City of Stockton used for previous time steps</td>
</tr>
<tr>
<td>Exp_oth_est</td>
<td>State variable</td>
<td>Estimated Delta diversions by Contra Costa WD and the City of Stockton used for current time step</td>
</tr>
<tr>
<td>VernWQ</td>
<td>State variable</td>
<td>San Joaquin River salinity (EC) at Vernalis</td>
</tr>
<tr>
<td>int</td>
<td>State variable</td>
<td>Days in month</td>
</tr>
<tr>
<td>xx_EC_STD</td>
<td>State variable</td>
<td>Bay-Delta Plan water quality standard for station xx</td>
</tr>
<tr>
<td>Line_xx_lo</td>
<td>State variable</td>
<td>Lower range for which ANN is applied for station xx</td>
</tr>
<tr>
<td>Line_xx_hi</td>
<td>State variable</td>
<td>Upper range for which ANN is applied for station xx</td>
</tr>
<tr>
<td>int</td>
<td>State variable</td>
<td>Station indicator</td>
</tr>
<tr>
<td>YearType</td>
<td>State variable</td>
<td>yyy</td>
</tr>
</tbody>
</table>

Key: ANN=Artificial Neural Network; EC=electrical conductivity, RM=river mile.

8.1.2 ANN Output

SacWAM implements export-inflow relationships for salinity control using ANN output that is referenced by the following six UDCs: UDC\ANN\meetJP, UDC\ANN\meetEM, UDC\ANN\meetCO, UDC\ANN\meetRS1, UDC\ANN\meetRS2, and UDC\ANN\meetRS3.
These UDCs have the following form:

\[ QSOD < b + m \times QSacValley \]

where:

\( QSOD \) = combined flow at Banks and Jones pumping plants  
\( QSacValley \) = combined flow of Sacramento River at Hood and Yolo Bypass at Lisbon Weir  
\( b \) and \( m \) = coefficients determined by the ANN function AnnLineGenArray.

The coefficients \( b \) and \( m \) are determined separately for each of the four control stations within the Delta — Collinsville, Emmaton, Jersey Point, and Rock Slough. Due to the highly non-linear flow-salinity relationship at Rock Slough, the ANN calculates three separate sets of coefficients that represent a three-piece linearization of the relationship. This results in six separate constraints for \( QSOD \), one each for Collinsville, Emmaton, and Jersey Point, and three for Rock Slough.

Five types of Delta conditions may exist, as implied by the coefficients returned by the ANN and the resulting export-inflow relationship required to meet D-1641 water quality standards:

- Intercept (\( b \)) = 0, and slope (\( m \)) <= 0.001: Delta salinity is insensitive to Delta exports, salinity control is not possible, therefore, the inflow-export constraint is relaxed and exports are capped at 1,500 cfs (export cap).
- \( m < 0 \): the inflow-export constraint is relaxed and exports are capped at 1,500 cfs.
- \( m > 1 \): known as negative carriage water, required Delta outflow for salinity control diminished as exports increase, therefore, exports are unconstrained by salinity control requirements.
- \(-b/m < 15,000 \) cfs (or 12,000 in dry and critical years): the Sacramento Valley inflow to the Delta for salinity control is greater than 15,000 cfs (or 12,000 cfs) for zero exports, therefore, to prevent the release of large volumes of water from storage to meet salinity requirements, combined project exports are capped at 1,500 cfs, and the inflow-export constraint is relaxed.
- For all other values of \( b \) and \( m \), the export-inflow relationship is enforced.

For additional discussion of the ANN, see Section 7.8.

### 8.2 Contra Costa Water District

In order to fix Contra Costa WD Delta intake pumping to values from the CalSim II model, UDCs are used to fix a maximum value for Rock Slough (RS) pumping and the combination of Old River and Victoria Canal pumping (\( OR \) and \( VC \)). UDCs for fixing Los Vaqueros fills and releases are also in this section but are not active in the model at this time. See Section 7.2.18 for more description of Contra Costa WD operations.

### 8.3 City of Stockton

The City of Stockton has multiple sources of water and conjunctively manages surface water and groundwater to deliver treated water within the metropolitan area. The City purchases treated water from Stockton East WD and also owns and operates its own WTP and associated intake located on the
San Joaquin River near Empire Tract. The UDC SEWD WTP limits water supplies from Stockton East WD to the 60 million gallon per day (mgd) capacity of the Joe Waidhofer WTP. Similarly, the UDC Delta WTP limits supplies from the City’s Delta WTP to its 30 mgd capacity. The UDC WR1485 further limits diversions from the Delta to be less than the discharge from the Stockton Regional WWTP as required by the City’s water right permit and by California Water Code section 1485.

8.4 Coordinated Operations Agreement

The COA, signed in 1986, defines formulae for sharing joint CVP-SWP responsibilities for meeting Delta standards (as the standards existed in SWRCB Water Right Decision 1485 [D-1485]) and other in-basin legal uses of water, and identifies how unstored flow is to be shared between the CVP and SWP. Additional details of COA are discussed in Section 7.2.10.

The implementation of COA in SacWAM requires the model to determine whether there is UWFE that may be shared by the CVP and SWP, or if there is IBU within the Sacramento Valley and Delta that must be met by storage releases from project reservoirs (or import of Trinity River water through the Clear Creek Tunnel). The existence of UWFE or IBU is determined by the UDC COA Balance that calculates the difference between project exports and project storage releases:

\[
UWFE - IBU = \text{DeltaSurplus}_{CVP} + \text{DeltaSurplus}_{SWP} + \text{CVP EXP1} + \text{CCWD EXP1} + \text{SWP EXP1} + \frac{2}{3} \times \text{NBA Art21} + \frac{2}{3} \times \text{NBA TableA} - \text{StorageRelease}_{SWP} - \text{StorageRelease}_{CVP} + \text{Unused FS} + \text{Unused SS}
\]

If the releases from project storage exceed project exports from the Delta, then there is IBU in the Sacramento Valley. Conversely, if Delta exports are greater than the change in storage, then there exists unused water for export. SacWAM uses the following definitions for these calculations:

- **Shasta Storage Release** = Sacramento below Keswick - Inflow to Shasta - Spring Creek Tunnel diversion
- **Folsom Storage Release** = American below Nimbus + Folsom South Canal + Folsom Lake diversions - Inflow to Folsom
- **Whiskeytown Storage Release/Trinity Import** = Clear Creek below Whiskeytown + Spring Creek Tunnel diversion – Natural inflow to Whiskeytown Reservoir
- **Oroville Storage Release** = Feather River below Thermalito - Inflow to Lake Oroville - Kelly Ridge Powerhouse flow - Thermalito Afterbay diversions - Power Canal diversions
- **CVP Delta Exports** = Export of CVP water at Jones Pumping Plant + Unused_SS
- **SWP Delta Exports** = Export of SWP water at Banks Pumping Water + Unused_FS + \(\frac{2}{3}\)*Table A and Article 21 water delivered from the North Bay Aqueduct

The ability of the projects to use their share of water under COA may be limited by the physical and permitted capacities of the pumping plants and by other regulatory constraints. The decision variables **Unused FS** and **Unused SS** represent one project’s use of the other project’s water in instances when...
either the CVP or SWP cannot export their share of water because of export capacity or regulatory restrictions. The user-defined integer int_Unused_FS_SS and the associated pair of UDCs, int_Unused_FS_SS Eqn1 and int_Unused_FS_SS Eqn2, prevent both Unused_FS and Unused_SS having non-zero values in the same time step.

Delta outflow is divided into the part that is required to meet regulatory requirements, which is part of IBU, Delta outflow that is surplus to regulatory requirements. Delta outflow is further divided into CVP share (Delta-Surplus_CVP) and SWP share (Delta-Surplus_SWP).

The user-defined integer, Int_IBU_UWFE, and the associated pair of UDCs, IBU_force and UWFE_force, prevent IBU and UWFE from both having non-zero values in the same time step.

The COA defines sharing formula for dividing UWFE between the two projects and assigning responsibilities for meeting IBU. The CVP is entitled to 55 percent of UWFE and SWP entitled to 45 percent of UWFE. The CVP is responsible for meeting 75 percent of IBU; the SWP is responsible for meeting the remaining 25 percent of IBU. The sharing formula are implemented in SacWAM using the UDCs COA_CVP and COA_SWP that are reproduced below.

\[
\begin{align*}
CVP\_EXP1 + CCWD\_EXP1 + Unused\_FS &= StorageRelease\_CVP - 0.75*IBU + 0.55*UWFE - \Delta Surplus\_CVP \\
SWP\_EXP1 + (2/3)* NBA\_Art21 + (2/3)* NBA\_TableA + Unused\_SS &= StorageRelease\_SWP - 0.25*IBU + 0.45*UWFE - \Delta Surplus\_SWP
\end{align*}
\]

Priorities in SacWAM have been set-up so that the CVP south-of-Delta operations are determined prior to SWP south-of-Delta operations. The UDC EI Split CVP prevents the CVP from using more than 50 percent of the available export capacity when the D-1645 export to inflow ratio is binding project operations. Similarly, the UDC OMR_BO_Actions \textbackslash OMR Constraints \textbackslash ShareAvailableExport prevents the CVP from using more than 50 percent of the available export capacity when export pumping is limited by OMR flow criteria.

### 8.5 Delta Cross Channel

The DXC is a gated diversion channel off the Sacramento River near Walnut Grove. The channel is operated to improve water quality in the interior and south Delta, and to improve the transfer of water from the Sacramento River to CVP and SWP export pumps in the south Delta. When the gates are open, water flows from the Sacramento River through DXC to the lower Mokelumne River and San Joaquin River. Water from the Sacramento River also flows through Georgiana Slough to the Mokelumne River.

When the DXC gates are open, flows through the channel are determined by the upstream stage in the Sacramento River. The flow may be estimated using the following empirical regression equation:

\[
Q\_DXC \text{ [cfs]} = 0.1896 \times QSac\_WG \text{ [cfs]} - 36
\]
where:

\[ Q_{DXC} = \text{Delta Cross Channel flow} \]
\[ Q_{Sac\_WG} = \text{Sacramento River flow at Walnut Grove} \]

D-1641 (SWRCB, 1999) and the NMFS (2009) BiOp specify when the DXC gates must be closed to improve migration of anadromous fish species through the Delta. Additionally, Reclamation procedures call for the gates to be closed when flows in the Sacramento River reach the 20,000 to 25,000 cfs range. For modeling purposes, SacWAM uses a Sacramento River flow threshold of 25,000 cfs for gate closure. The following set of equations are used in SacWAM to disaggregate flows in the Sacramento River into components above and below the flow threshold for gate closure of 25,000 cfs:

\[ Q_{Sac\_WG} = 25,000 + SAC\_above - SAC\_below \]
\[ SAC\_above < \text{int\_SAC\_above} \times 999,999 \]
\[ SAC\_below < 999,999 - \text{int\_above} \times 999,999 \]

The user-defined integer variable \text{int\_above} can either be zero or one. A value of zero indicates that the Sacramento River flow is below the 25,000 cfs threshold by an amount \text{SAC\_below}. A value of one indicates that the Sacramento River flow is above the threshold by an amount \text{SAC\_above}.

Finally, flow through the DXC is calculated using the following equation:

\[ Q_{DXC} = [0.1896 \times 25,000 \times (1 - \text{int\_above}) - 36 \times (1 - \text{int\_above}) - 0.1896 \times \text{SAC\_below}] \times DXC\_fraction \]

where:

\[ DXC\_fraction = \text{number of days in the month that the DXC is open, expressed as a fraction.} \]

8.6 Delta Export Constraints

The UDCs under \textit{Delta Export Constraints} implement CVP and SWP Delta pumping limits described in Chapter 7. \textit{Delta Export Constraints} work in conjunction with \textit{Split Exports} (see Section 8.19), such that export limits apply only to the portion that is pumped directly from the Delta (as opposed to exports that may be diverted around/under the Delta through an Isolated Facility).

8.6.1 April May Pulse Period

D-1641 restricts export pumping during a 31-day pulse period in April and May depending on flows in the San Joaquin River at Vernalis. During the pulse period, exports may not exceed 1,500 cfs, or 100 percent of the 3-day running average of Vernalis flow, whichever is greater. In SacWAM, the two UDCs \textit{AprilMayPulse\_CVP} and \textit{AprilMayPulse\_SWP} restrict CVP and SWP exports from the south Delta to be less than pulse period requirements.

8.6.2 D-1641 EI Ratio

D-1641 requires Reclamation and DWR to comply with an export limit objective to restrict CVP and SWP export rates from the Delta. The E/I ratio is measured as the average 3-day export rate for the SWP...
Clifton Court intake and CVP Jones Pumping Plant divided by the estimated average inflow to the Delta over a 3-day or 14-day period. Delta Exports are constrained to being less than or equal to Delta Inflow multiplied by the export ratio, ExpRatio.

8.6.2.1 Delta Inflow Eqn

Delta Inflow is defined as a standard LP variable (i.e., must be zero or positive). The UDC Delta Inflow Eqn sets the Delta Inflow to be equal to the sum of the Sacramento River at Freeport, wastewater discharge from the Sacramento Regional WWTP, San Joaquin River at Vernalis, Calaveras River below New Hogan Dam, Cosumnes River at Michigan Bar, Mokelumne River below Woodbridge, Sacramento Weir spills, Fremont Weir spills, Cache Creek at Rumsey, and South Fork Putah Creek at Interstate 80. This measure of Delta inflow follows that defined in D-1641 (SWRCB, 2000), with the following exceptions:

- SacWAM uses Calaveras River flow below New Hogan Dam rather than flow at Bellota as specified in D-1641.
- SacWAM does not include inflow from miscellaneous streams (Bear Creek, Dry Creek, Stockton Diverting Canal, French Camp Slough, Marsh Creek, and Morrison Creek) as specified in D-1641.

These changes from D-1641 are consistent with how DWR and Reclamation operate the CVP and SWP to meet SWRCB regulatory requirements (Chu, 2016).

8.6.2.2 EI Split CVP

SacWAM assumes that available export capacity under the E/I requirement is shared equally between the CVP and SWP, unless one project is unable to pump its share of water. The UDC EI Split CVP restricts CVP exports of the federal share of available Delta water to be less than one-half of the available regulatory export capacity.

8.6.2.3 EI Split SWP

No separate limit is set on SWP exports under the E/I ratio as CVP south-of-Delta deliveries have a higher priority in SacWAM than SWP south-of-Delta deliveries. Within each time step, CVP operations are simulated first. The UDC EI Split SWP is turned off.

8.6.3 SJR EI Ratio

The NMFS (2009) BiOp established export restrictions to reduce the vulnerability of emigrating Central Valley steelhead within the lower San Joaquin River to entrainment into the channels of the South Delta caused by CVP and SWP export pumping. Under RPA Action IV.2.1, from April 1 to May 31 CVP and SWP exports are restricted to a fraction or a ratio of the San Joaquin River flow at Vernalis. The ratio is based on the San Joaquin River index. Details of the pumping restriction are described in Chapter 7.

The UDC SJR_EIRatio_Total restricts combined CVP and SWP exports to be less than the state variable Other\Ops\ExportOps\SJ_Ratio\SJ_MaxExp.

The UDC SJR_EIRatio_CVP restricts CVP pumping of the federal share of available Delta water to be less than one-half of Other\Ops\ExportOps\SJ_EIRatio\SJ_MaxExp.
8.7 Delta Reverse Flows

The WEAP modeling software does not allow bi-directional flow in rivers. However, there are two channel reaches within the Delta where bi-directional flows must be simulated. The first channel reach is the combined flow in OMR between the intake to the DMC/Jones Pumping Plant and the confluence of OMR and San Joaquin River. The second channel reach is flow in the lower San Joaquin River above its confluence with the Sacramento River (QWest).

SacWAM uses two parallel river arcs to represent bi-directional flow and an associated pair of equations to restrict flows so that water can move in only one direction during a single time step. The form of the equations is as follows:

\[
Q_{\text{Downstream}} \leq \text{Integer}_{\text{ReverseFlow}} \times 999,999
\]

\[
Q_{\text{Upstream}} \leq 999,999 - \text{Integer}_{\text{ReverseFlow}} \times 999,999
\]

Where \( Q_{\text{Downstream}} \) is the natural (positive) flow direction, \( Q_{\text{Upstream}} \) is the reverse flow direction, and \( \text{Integer}_{\text{ReverseFlow}} \) is an integer decision variable that has a value of either 0 or 1. If \( \text{Integer}_{\text{ReverseFlow}} \) equals 0, flow is in the natural direction; reverse flow occurs when \( \text{Integer}_{\text{ReverseFlow}} \) equals 1.

8.7.1 Old and Middle River (OMR)

The user-defined decision variable OMR Net Flow represents the net combined flow in the Old and Middle Rivers at Bacon Island at the location of the USGS gauges used for compliance purposes. Net flow is calculated as OMR Positive Flow minus OMR Reverse Flow. When the integer variable OMR_Int has value of 1, there is no reverse flow. During model testing, the requirement that flow in one channel be zero often caused difficulties for the MILP solver. Therefore, these requirements are currently relaxed in SacWAM.

8.7.2 QWest

Qwest is defined as the net westward flow of the San Joaquin River at Jersey Point averaged over a tidal cycle. Under natural conditions Qwest is positive. However, under certain tidal, river inflow, and south Delta export pumping conditions, net reverse flows may occur, i.e., the net flow direction is eastward. Negative values of Qwest occur when Delta diversions and agricultural demands in the south and central Delta exceed the inflow into the central Delta. Qwest is typically positive during wetter water years and always positive in the spring. Qwest is typically negative in the summer of drier years. Qwest criteria are not included in the 1995 Bay-Delta Plan (SWRCB, 1995); however, Qwest criteria have previously been considered as a regulatory parameter for protection of central Delta fish.

In SacWAM, Qwest reverse flow is represented as an outflow from the Sacramento River upstream from the confluence. Qwest positive flow is represented as the San Joaquin River below the OMR confluence. During model testing, the requirement that flow in one channel be zero often caused difficulties for the MILP solver. Therefore, these requirements are currently relaxed in SacWAM.

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SacWAM represents the Old River and Middle River as a single river.
8.8 Delta SOD Channels

Flow requirements for OMR established by USFWS (2008) may limit export pumping from December 15 to June 30. However, SacWAM cannot simulate the tidal hydrodynamics of the south Delta. Instead, the model uses a set of empirical regression equations and a flow balance to determine OMR flows. Hutton (2008) developed flow relationships for south Delta channels based on the following flow balance:

\[
\text{OMR} = \text{SJR}_v + \text{IS}_{\text{OR}} - \text{SJR}_{\text{HOR}} - \text{CCF} - \text{JPP} - \text{CCWD} - \text{NCD}_{\text{SD}}
\]

where:

- \(\text{SJR}_v\) = San Joaquin River at Vernalis
- \(\text{SJR}_{\text{HOR}}\) = San Joaquin River downstream from Head of Old River
- \(\text{IS}_{\text{OR}}\) = Indian Slough at Old River
- \(\text{CCF}\) = Clifton Court Forebay diversion
- \(\text{JPP}\) = Jones Pumping Plant diversion
- \(\text{CCWD}\) = Contra Costa WD Old and Middle River diversion
- \(\text{NCD}_{\text{SD}}\) = Net channel depletion in the South Delta

Assuming a linear relationship between San Joaquin River flow at Vernalis and the flow at the Head of Old River, the flow balance can be rewritten as:

\[
\text{OMR} = A*\text{SJR}_v + B*(\text{CCF} + \text{JPP} + \text{CCWD} + \text{NCD}_{\text{SD}}) + C
\]

The value of the coefficients \(A\), \(B\), \(C\), as reported by Hutton (2008), are listed in Table 8-2.

<table>
<thead>
<tr>
<th>Barriers</th>
<th>Grant-Line Canal</th>
<th>San Joaquin River at Vernalis (cfs)</th>
<th>Coefficients</th>
</tr>
</thead>
<tbody>
<tr>
<td>Out</td>
<td>Out</td>
<td>&lt; 16,000</td>
<td>0.471</td>
</tr>
<tr>
<td>Out</td>
<td>Out</td>
<td>16,000 – 28,000</td>
<td>0.681</td>
</tr>
<tr>
<td>Out</td>
<td>Out</td>
<td>&gt;28,000</td>
<td>0.633</td>
</tr>
<tr>
<td>In (Spring)</td>
<td>Out/In</td>
<td>All</td>
<td>0.419</td>
</tr>
<tr>
<td>In (Fall)</td>
<td>Out/In</td>
<td>All</td>
<td>0.238</td>
</tr>
</tbody>
</table>

8.8.1 Q_SOD

\(Q_{\text{SOD}}\) is a user-defined standard LP variable that represents combined diversions and exports from the south Delta. The UDC \(\text{Set}Q_{\text{SOD}}\) determines \(Q_{\text{SOD}}\) as the sum of the headflows in the California Aqueduct and DMC, CCWD OMR diversions, and south-of-Delta net consumptive use.

8.8.2 Q_IndianSlough

\(Q_{\text{IndianSlough}}\) is a user-defined standard LP variable that represents flow from the San Joaquin River through Indian Slough to the Old River, at a point south of the OMR flow compliance location (\(\text{Set}Q_{\text{IndianSlough}}\)). The constraint \(\text{Set}Q_{\text{IndianSlough}}\) constrains flow through Indian Slough to be equal to \((1+\text{coefB})*Q_{\text{SOD}}\) based on the Hutton (2008) relationships described above.
8.8.3 Q_HOR

Q_HOR is a user-defined standard LP variable that represents flow at HOR (Set Q_HOR 1). The constraint Set Q_HOR 2 constrains flow at HOR to be equal to \( \text{coefA} \times Q_{SJ} + \text{coefC} \), based on the Hutton (2008) relationships described above, where \( Q_{SJ} \) is the flow in the San Joaquin River at Vernalis.

8.9 Delta Salinity

The purpose of the LP variables and UDCs defined under Delta Salinity is to calculate the outflow requirement for salinity control. This requirement is needed for the COA balance as it is part of IBU that the CVP and SWP are jointly obligated to meet.

8.9.1 Compliance Stations

The user-defined decision variables \( CO \), \( EM \), \( JP \), \( RS1 \), \( RS2 \), and \( RS3 \) represent the outflow required to meet D-1641 water quality standards at Collinsville, Emmaton, Jersey Point, and Rock Slough.\(^{21} \) The value of these variables are determined by UDCs (setCO, setEM, setJP, setRS1, setRS2, and setRS3) using the ANN export to inflow relationship for water quality compliance and a Delta flow balance.

8.9.2 Delta Flow Balance

The required Delta outflow for salinity control is calculated from a flow balance. Components of this flow balance are as follows:

- \( \text{DeltaExports} = \) Diverted inflow to the California Aqueduct and Delta-Mendota Canal
- \( \text{DeltaFlows} = \) Delta inflow from the San Joaquin River, Littlejohn Creek, Calaveras River, Mokelumne River, Kellogg Creek, and Marsh Creek
- \( \text{MiscFlows} = \) Delta diversions/exports at Barker Slough Pumping Plant, Old River Pipeline intakes on the Old River and Victoria Canal, Contra Costa Canal intake on Rock Slough
- \( \text{Net DICU} = \) Net Delta island consumptive use of net channel depletion

8.9.3 Outflow for Salinity Control

The user-defined variable \( \text{OutflowRequirement} \) is the net Delta outflow required for salinity control. It is the maximum of the outflow needed for compliance at the individual stations. This is enforced using a set of seven UDCs (\( \text{OR eqn1, OR eqn2, OR eqn3, OR eqn4, OR eqn5, OR eqn6, and OR eqn7} \)).

8.10 Feather River Service Area

Two UDCs relate to operation of canals within the FRSA. These are described in the sections below.

\(^{21} \) The D-1641 salinity requirement at Rock Slough is represented using three variables because of piecewise linear approximation of the inflow to export relationship for salinity control.
8.10.1 Western Canal Outflow

Based on a 1922 agreement, Western Canal WD supplies water to managed wetlands located in the Butte Sink. After September drainage of rice fields, up to 200 cfs of water is released from the Western Canal to Butte Creek to achieve a flow rate at Sanborn Slough of 250 cfs. From 2000 to 2009, these releases averaged approximately 14 TAF/year.

In SacWAM, the desired Western Canal release is defined by the state variable Western Canal Outflow. When the flow in Butte Creek near Chico (USGS gauge 11390000) is less than 15 TAF/month, Western Canal Outflow is set to 40 cfs in September, 140 cfs in October, and 30 cfs in November. In all other months the release is set to zero. These flow objectives are imposed by the UDC Western Canal Outflow constraint. The release requirements to Butte Creek are modeled using a UDC rather than using WEAP’s flow requirement object, in order to limit flows to Butte Creek to the desired target.

8.10.2 Cox Spill

The Joint Board Canal conveys water from the Thermalito Afterbay to four water districts that collectively are known as the Joint Water District: Biggs-West Gridley WD, Butte WD, Richvale ID, and Sutter Extension WD. Excess water in the Joint Board Canal is spilled back to the Feather River through a wasteway known as the Cox Spill. Based on an analysis of canal data from 2000 to 2009 (NCWA, 2014), Cox Spill flows are set at 1.5 percent of the Joint Board Canal diverted inflow. This is equivalent to approximately 9 TAF/year.

8.11 Fix Leaks

WEAP diversion arcs are used in SacWAM to represent canals, channels, and pipelines that deliver water from a stream or river to a demand site or catchment object. For example, the Foothill WTP arc connects the Sacramento River to demand sites U_02_SU and U_03_SU, which represent the City of Redding on the west and east bank of the Sacramento River. In certain high flow situations, SacWAM may wish to remove water from the system by diverting water in excess of demand through the Foothill WTP arc and out of the model domain.

Five UDCs are used to prevent outflow from the model domain for the following diversion arcs: Bella Vista (Pipeline), Foothill WTP, TCC (Tehama-Colusa Canal), GCC (Glenn-Colusa Canal) and El Dorado Hills WTP. In this manner, excess water flows to the Delta and leaves the model domain as surplus Delta outflow. A sixth UDC is implemented in the model to prevent Contra Costa WD intake pumping from leaving the system rather than meeting deliveries (Old River Pipeline).

8.12 Freeport Regional Water Project

EBMUD undertook the Freeport Regional Water Project in partnership with Sacramento County WA. The project enables EBMUD to take delivery of CVP water to meet a portion of its drought year water demands. The CVP contract allows EBMUD to divert up to 133,000 acre-feet of American River water each year with a total not to exceed 165,000 acre-feet in three consecutive years. This diversion can only occur in years when EBMUD’s total system storage is forecast to be less than 500,000 acre-feet. The maximum diversion rate is 100 mgd.
The UDC Freeport_EBMUD limits EBMUD’s use of Freeport to the user-defined variable FPT_Diversion as described in Chapter 7.

### 8.13 Glenn-Colusa Canal

Glenn-Colusa ID sells district water to the Colusa Basin Drain water users. In SacWAM, these users are represented by demand unit A_08_PA. Water sales are delivered from the Glenn-Colusa Canal. The UDC Glenn Colusa ID limits the sale of water to that available to Glenn-Colusa ID under the district’s water rights and CVP contract, less the amount of water delivered to district farmers.

### 8.14 Knights Landing Ridge Cut

The Knights Landing Ridge Cut (Ridge Cut) was constructed to provide an outlet from the Colusa Basin when high Sacramento River stage prevents discharge of excess water through the Knights Landing Outfall Gates. The Ridge Cut, which passes through the Knights Landing Ridge, consists of two dredged channels with a center island. The Ridge Cut has a total width of approximately 400 feet, and a capacity of 15,000 to 20,000 cfs. Floodwater, which would otherwise have ponded between the back levee along the east side of Colusa Basin Drain and higher ground to the west, flows through the Ridge Cut into the Yolo Bypass. The Ridge Cut also provides irrigation water during the summer months. Flows through the Ridge Cut are ungauged; however, DWR estimates flows based on the stage at the Knights Landing Outfall Gates. During the summer, water levels in the Ridge Cut are controlled by a temporary weir at the southern end of the channel to facilitate irrigation diversions.

SacWAM defines the LP variables CBD and KRLC to represent outflow from the drain to the Sacramento River and flow through the Ridge Cut, respectively. The user-defined decision variable QSac represents flow in the Sacramento River below Wilkins Slough at the Navigation Control Point. This flow is divided into two components, QSac_0 and QSac_1, which represent flow up to a 15,000 cfs threshold and the flow above this threshold. SacWAM uses an integer variable, Int_KLRC, and a set of equations to divide the flows, as follows:

\[
Q_{Sac,0} \leq Int_{KLRC} \times 9,999,999
\]

\[
Q_{Sac,1} \leq 9,999,999 - Int_{KLRC} \times 9,999,999
\]

\[
Q_{Sac} = Q_{Sac,0} + Q_{Sac,1} + 15,000 \times Int_{KLRC}
\]

Outflow through the Colusa Basin Drain to the Sacramento River is restricted when flows in the Sacramento River exceed 15,000 cfs.

\[
CBD < 9,999,999 - Int_{KLRC} \times 9,999,999
\]

The historical flow through the Ridge Cut is stored in a csv file and assigned to the state variable KLRCmax. Under normal, non-flood, operations, flow through the Ridge Cut is constrained to be less than the historical flow, and all remaining flow discharges from the Colusa Basin Drain into the Sacramento River at Knights Landing. An IFR on the Ridge Cut equal to the historical flow is used to achieve the desired operation.
8.15 Los Vaqueros Reservoir

Los Vaqueros Reservoir is an offstream facility owned and operated by Contra Costa WD for water blending purposes and to provide an emergency water supply. The reservoir is filled from district intakes on the Old River and Victoria Canal.

Simulation of Los Vaqueros Reservoir has not been fully implemented in SacWAM. UDCs defined under Los Vaqueros Reservoir simply restrict filling and releasing of water from the reservoir in the same time step.

8.16 Minimum GW Pumping

Typically, SacWAM demand units are supplied with a mix of surface water and groundwater. Surface water is usually assigned the first supply preference and groundwater assigned the second supply preference. In the model, a minimum groundwater pumping fraction acts as a surrogate for representing those lands within the demand unit that are dependent on groundwater—not having access to surface water. The fraction is calculated from DWR’s county land use surveys in which each agricultural parcel is assigned a source of water: surface water, groundwater, or mixed. The fraction is set equal to the area of lands supplied by groundwater divided by the total area of irrigated lands. Applied water demands in excess of minimum groundwater pumping are met from surface water and additional groundwater pumping, if necessary.

In cases where SacWAM demand units are supplied from only one surface water transmission link, surface water deliveries are constrained using the WEAP transmission link property Maximum Flow Percent of Demand. This is set equal to (1−minimum groundwater pumping factor). In cases where a demand unit is supplied from multiple surface water transmission links, the constraint on surface water use must be imposed using a UDC. The form of the UDC is as follows:

\[ \sum(\text{Flow through transmission links}) < (1-\text{minimum groundwater pumping factor}) \times \text{supply requirement} \]

The minimum groundwater pumping factors and supply requirements for each DU are listed under Demand Sites and Catchments\[DU name\].

8.17 Mokelumne

Pardee and Camanche reservoirs are owned and operated by EBMUD to meet flood control requirements specified in the USACE flood-control manual. These requirements are in place from September 15 to August 1. During this period, required flood space is divided into a rain-flood reservation and a snowmelt flood reservation. The maximum flood control space is 200,000 acre-feet, with a minimum of 130,000 acre-feet of space to be provided in Pardee and Camanche reservoirs. Up to 70,000 acre-feet may be provided by available space in PG&E’s Salt Spring and Lower Bear reservoirs, which are located in the upper watershed.

The UDC FloodControl requires that the difference between combined Pardee and Camanche storage capacity and the volume in storage is less than the flood space requirement as calculated by the state variable Other\Ops\Mokelumne\FloodSpaceRequirement. This is further discussed in Chapter 7.
8.18 OMR BO Actions

OMR Reverse Flow is a user-defined standard LP variable (i.e., must be zero or positive) that represents reverse flow in OMR at the USGS compliance locations adjacent to Bacon Island. The UDC Set Q_OMR_Final restricts the reverse flow (i.e., from North to South) to be less than the state variable Other\OMR and Health and Safety\Q_OMR.ReverseBound. This is further described in Chapter 7. The UDC ShareAvailableExport restricts diversions at Jones (CVP) pumping plant to 50% of available export capacity under the OMR standard (Other\OMR and Health and Safety\Available Export), so that available pumping capacity is split equally between CVP and SWP.

8.19 Oroville Fall Operations

October and November flows in the Feather River high-flow channel (i.e., downstream from the Thermalito Afterbay release to the river) are constrained to be less than 4,000 cfs in October and 2,500 cfs in November, except when Oroville is spilling (Fall release constraint). This is an operational constraint in place to prevent triggering of increased November to March flow requirements under the 1983 MOU between DWR and CDFW (formerly California Department of Fish and Game). See Section 7.2.3.4 for more description of this operation.

8.20 San Luis Reservoir

San Luis Reservoir is a joint CVP-SWP offstream storage facility used to temporary store project water before delivery to project contractors. In SacWAM, it is represented as two separate reservoirs: CVP_SanLuis and SWP_SanLuis.

8.20.1 CVP_SanLuis

Water from DMC is delivered to San Luis Reservoir through the O’Neill and Gianelli pumping-generating plants. CVP water from San Luis Reservoir is subsequently released into the San Luis Canal or to the DMC for delivery to CVP contractors. Additionally, the CVP diverts water from the west end of San Luis Reservoir through the Pacheco Tunnel and Pacheco Conduit to supply CVP water service contractors in Santa Clara and San Benito counties.

SacWAM’s simulated operations of the CVP share of San Luis Reservoir are driven by the CVP San Luis rule curve. During the fall, winter, and spring the reservoir is filled up to rule curve with a mix of unstored water supplies and storage releases from CVP reservoirs. Subsequently, if additional unstored water supplies exist, the reservoir is filled above rule curve, up to capacity, according to the amount of water available. Lastly, CVP may use any unused State Share of water under COA to fill the CVP share of the reservoir to capacity.

The user-defined variable CVPSanLuisInt is an integer variable associated with CVP simulated operations of San Luis Reservoir. The associated UDCs Fill and Release prevent the reservoir from both filling and draining in the same time step.

8.20.2 SWP_SanLuis

The SWP share of San Luis Reservoir allows DWR to meet peak seasonal SWP demands. DWR stores water in the reservoir when pumping at Banks Pumping Plant exceeds SWP contractor demands, and
releases water to the San Luis Canal/California Aqueduct when pumping at Banks Pumping Plant is insufficient to meet these demands.

SacWAM’s simulated operations of the SWP share of San Luis Reservoir are driven by the SWP rule curve for the reservoir. During the fall, winter, and spring the reservoir is filled up to rule curve with a mix of unstored water and storage releases from Lake Oroville. Subsequently, if additional unstored water supplies exist, San Luis Reservoir is filled above rule curve, up to the SWP’s share of capacity according to the amount of water available. Lastly, SWP may use any unused Federal Share of water under COA to fill the reservoir.

The user-defined variable \( SWPSanLuisInt \) is an integer variable associated with CVP simulated operations of San Luis Reservoir. The associated UDCs \( \text{Fill} \) and \( \text{Release} \) prevent the reservoir from both filling and draining in the same time step.

### 8.21 Split Exports

The UDCs under Split Exports disaggregate Delta exports into different flow components. Variables defined under \( \text{Split Exports} \) are referenced by \( \text{Delta Export Constraints} \) (see Section 8.6) and by COA (see Section 8.4).

#### 8.21.1 WaterFix

Flows through Banks and Jones pumping plants are disaggregated for the purposes of implementing D-1641 standards and BiOp requirements under a simulated scenario that includes the Water Fix (i.e., the Delta Tunnels originally envisaged as part of the Bay Delta Conservation Plan (BDCP)). For example, restrictions on Delta pumping in order to satisfy OMR flow requirements and the Export-to-Inflow ratio are applied only to the portion of exports that are derived directly from the Delta. Disaggregated flows consist of a ‘through-Delta’ component and an ‘isolated facility’ component. User-defined variables for the various export components are listed in Table 8-3.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CA_TD</td>
<td>The portion of flows into the California Aqueduct derived from the Delta</td>
</tr>
<tr>
<td>CA_IF</td>
<td>The portion of flows into the California Aqueduct that is diverted around the Delta through the IF</td>
</tr>
<tr>
<td>DM_TD</td>
<td>The portion of flows into the DMC derived from the Delta</td>
</tr>
<tr>
<td>DM_IF</td>
<td>The portion of flows into the DMC that is diverted around the Delta through the IF</td>
</tr>
<tr>
<td>CA_exp</td>
<td>Total flows into the California Aqueduct.</td>
</tr>
<tr>
<td>DM_exp</td>
<td>Total flows into DMC</td>
</tr>
<tr>
<td>Export_TD</td>
<td>Total combined flows into the California Aqueduct and DMC that come from the Delta</td>
</tr>
<tr>
<td>Export_IF</td>
<td>Total combined flows into the California Aqueduct and DMC that are diverted around the Delta through the IF</td>
</tr>
<tr>
<td>CC_TD</td>
<td>The portion of Contra Costa Water District diversions derived from the Delta</td>
</tr>
</tbody>
</table>

Key: DMC=Delta-Mendota Canal; IF=Isolated Facility.

#### 8.21.2 North Bay Aqueduct

Water pumped from the Barker Slough Pumping Plant into the North Bay Aqueduct is a mix of SWP contract water and water right water. User-defined variables for the various water types include: Table A Water, Article 21 Water, Vallejo Permit Water, and Settlement Water. Permit Water and Settlement Water are described below.
In 1998, the Cities of Fairfield, Benicia, and Vacaville filed applications with SWRCB to appropriate a total of 31,620 acre-feet. This water would be wheeled through North Bay Aqueduct facilities. DWR, the City of Vallejo, and others protested these applications. In a subsequent settlement agreement between DWR, Solano County WA, and the three applicants, DWR agreed to deliver up to 31,620 acre-feet to the applicants. This water, known as “settlement water”, is not available when SWRCB Term 91 is in effect.

The City of Vallejo holds a water right (Permit 8993) issued in 1948 for the diversion of up to 31.52 cfs year-round from Cache Slough, primarily for M&I purposes. This is equivalent to a maximum of 22,780 acre-feet per year. Through contracts and agreements, DWR has limited the annual amount of permit water to 17,287 acre-feet. Permit water is senior to SWP water rights, and is not subject to Term 91 curtailments.

8.22 Weirs

Six weirs, all located along the Sacramento River, are included in SacWAM. Flows over these weirs are calculated using a fixed fraction of Sacramento River flow above a defined threshold at each weir location. This requires the use of integer variables to determine flow conditions within the Sacramento River at each weir within the current time step. The values of the integer variables are equal to 1 when flow thresholds are exceeded and equal to zero otherwise. The flow thresholds and fractions of flows above these thresholds that spill over the weirs are presented in Table 8-4.

For each weir, there is a UDC named $Q_{[weirname]}_HistFix$. This constraint is for testing purposes only and is used to fix weir flows to historical values. These historical values are stored in the file Data\Param\SACVAL_WeirInflows.csv. If this is activated by the model user, all other weir constraints should be deactivated.

<table>
<thead>
<tr>
<th>Weir</th>
<th>Flow Threshold (cfs)</th>
<th>Fraction of Flow Above Threshold to Weir</th>
<th>Integer Variable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eastside to Butte Basin</td>
<td>90,000</td>
<td>0.73071</td>
<td>Int_eastside</td>
</tr>
<tr>
<td>Moulton Weir</td>
<td>60,000</td>
<td>0.33152</td>
<td>Int_moulton</td>
</tr>
<tr>
<td>Colusa Weir</td>
<td>30,000</td>
<td>0.76788</td>
<td>Int_colusa</td>
</tr>
<tr>
<td>Tisdale Weir</td>
<td>18,000</td>
<td>0.75177</td>
<td>Int_tisdale</td>
</tr>
<tr>
<td>Fremont Weir</td>
<td>62,000</td>
<td>0.79808</td>
<td>Int_fremont</td>
</tr>
<tr>
<td>Sacramento Weir</td>
<td>73,000</td>
<td>0.87380</td>
<td>Int_sacramento</td>
</tr>
</tbody>
</table>

An example of the implementation of the weir logic is provided by the Eastside weir spills. Floodwaters in the Sacramento River overflow the left bank of the river into Butte Basin at three sites in a reach known as the Butte Basin Overflow Area, or the Butte Basin Reach. The northernmost overflow point is at a degraded levee called the M&T flood relief structure. The second overflow point is the 3Bs natural overflow site. The last overflow point is at another degraded levee known as the Goose Lake flood relief structure. In SacWAM, these 3 structures are simulated as a single weir located downstream from the Sacramento River confluence with Stony Creek. Water spills into the Butte Basin when Sacramento River flows exceed 90,000 cfs. Sacramento River flows upstream from the weir (i.e., $QSac_{RM184}$) are split into two components: $QSac_{RM184}_0$ that represents flows up to 90,000 cfs; and $QSac_{RM184}_1$ that represents the incremental flows above 90,000 cfs.

$$ QSac_{RM184} = QSac_{RM184}_0 + QSac_{RM184}_1 $$
The weir equations are set up so that the integer variable, \( \text{Int}_{\text{eastside}} \), is forced to a value of one when flows are greater than 90,000 cfs, or a value of zero when flows are less than this threshold.

\[
QSac_{\text{RM184}_0} \leq 90,000 + 1
\]

\[
QSac_{\text{RM184}_0} \geq \text{Int}_{\text{eastside}} \times 90,000
\]

\[
QSac_{\text{RM184}_1} \leq \text{Int}_{\text{eastside}} \times 999,999
\]

Above the weir threshold, flows over the weir, \( Q_{\text{Overflow}} \), are a function of the incremental flow \( QSac_{\text{RM184}_1} \).

\[
Q_{\text{Overflow}} = 0.73071 \times QSac_{\text{RM184}_1}
\]