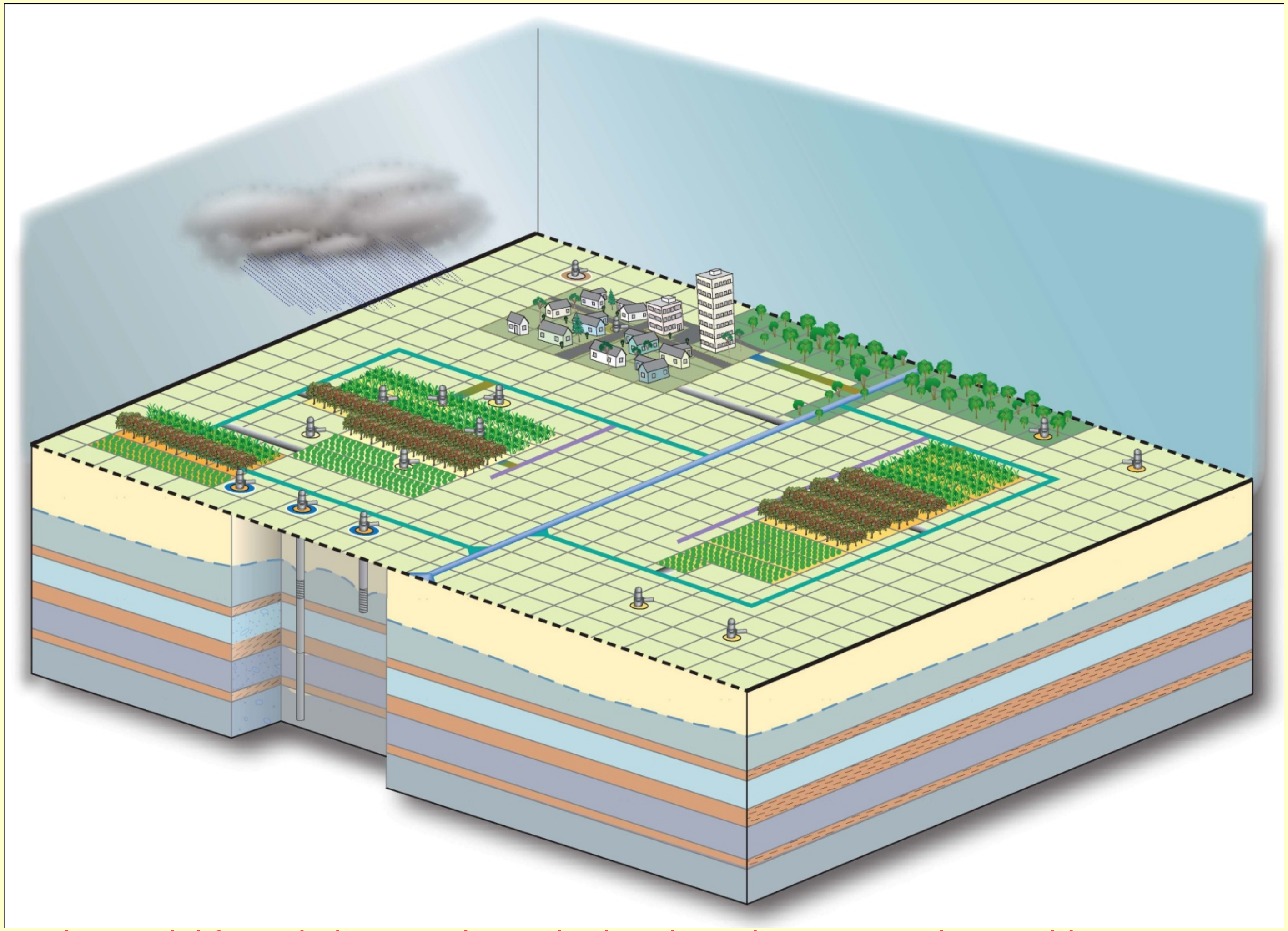
Conjunctive Use Analysis Using MODFLOW with the Farm Process

Peer Review Workshop, California Water and Environmental Modeling Forum--Sacramento, CA June 18, 2012



The model formulations, code, and related results presented are subject to change through model updates, upgrades, and/or refinements.

By Randy Hanson and Wolfgang Schmid

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What Do HYDROLOGIC MODELS Provide?

- Understanding of Regional Flow Systems
- Complete Assembly of Hydrologic-Budget Components
- Systematic Analysis of All Hydrologic Components
- Linkage between Databases, Monitoring Networks, Model Input Requirements, and Decision Makers
- Flexibility for testing Policies, Projects, & Remediation
- Vehicle for mediation between transboundary neighbors
- Systematic estimate of Uncertainty and Sensitivity
- Vehicle for Communication & Understanding

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Our Goal and Philosophy for Resource Simulation and Analysis → **ONE WATER !**

Sustainability: Development and use of water in a manner that can be maintained for an indefinite time without causing unacceptable environmental, economic, or social consequences.

Conjunctive Use: Joint use and management of surface-water and groundwater resources to maximize reliable supply and minimize damage to the quantity or quality of the resource.

Adaptation: Modification of use, movement, and storage of water to promote sustainability of water, food, and energy security that is physically, economically, politically, and socially feasible.

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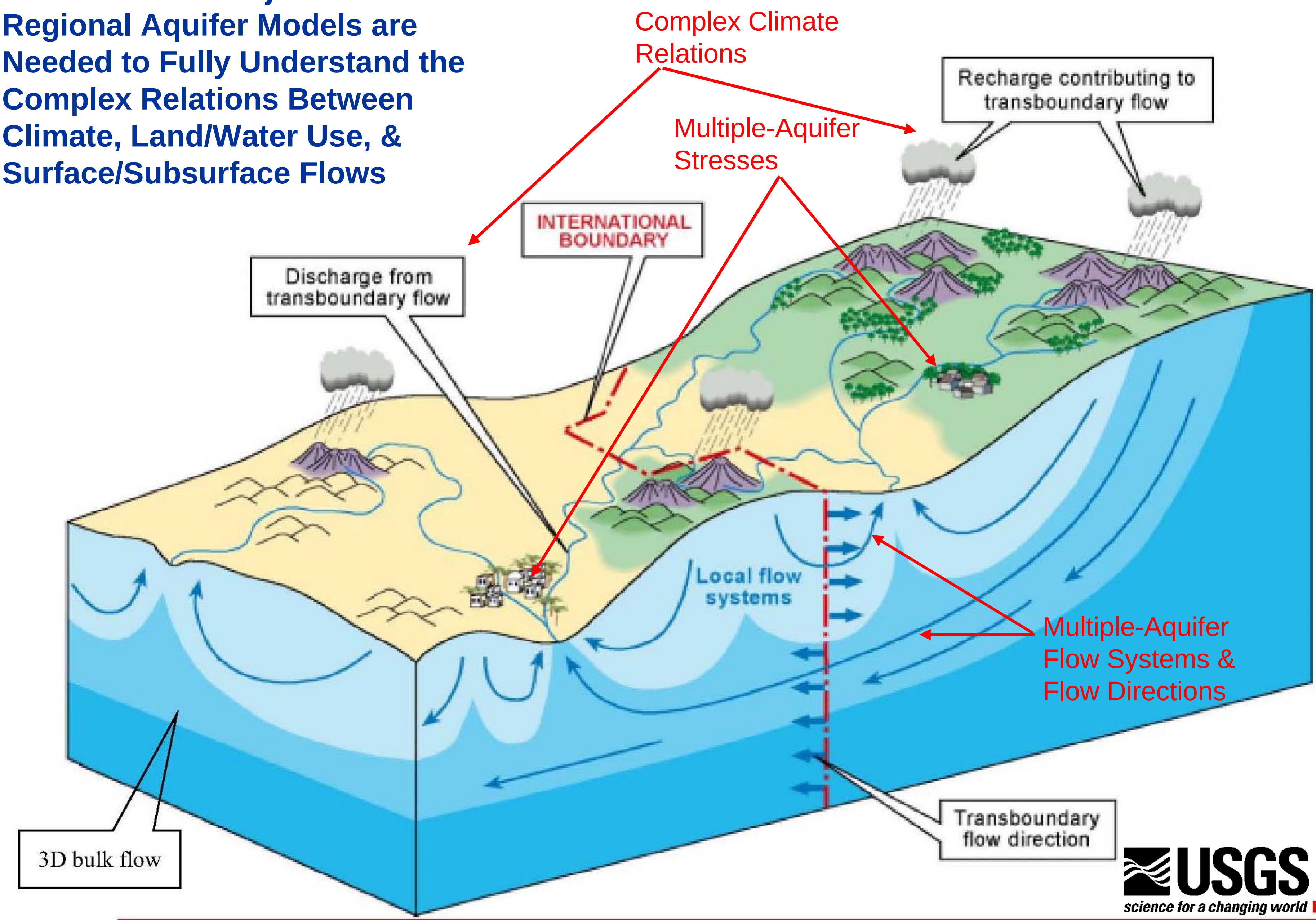
Simulation of Conjunctive Use with Regional Aquifer Models are Needed to Fully Understand the Complex Relations Between Climate, Land/Water Use, & Surface/Subsurface Flows



Modified from Puri & Arnold, 2002

Contents

- Theory of the Farm Process (FMP) for MODFLOW
- Features of MODFLOW2005-FMP2 (MF2005-FMP2)
- New & Future FMP Features
- Advantages & Limitations
- Selected Examples of FMP Uses
- Outlook for MODFLOW and Integrated-Hydrologic Modeling

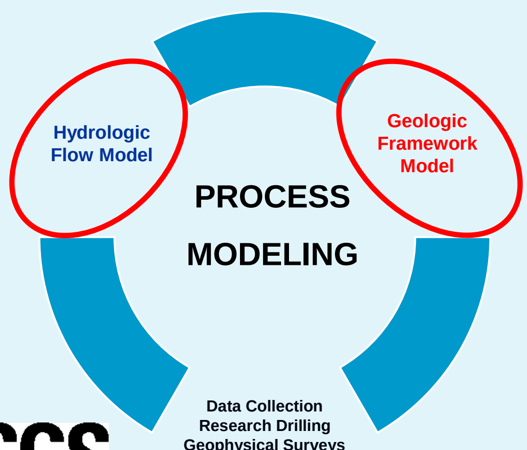
USGS MODFLOW → MODULAR EXPANSION

Ground-water Flow Model → Full Hydrologic Model

→ Coupled Hydrologic Models → Coupled Other Models

PROCESS MODELING

* Ground Water Flow Modeling
* Estimating Ground shaking
* Seismic Wave Propagation and Earthquake Relocation
* Fault Interactions and Tectonic Strain Accumulation
* Natural-Source Contamination



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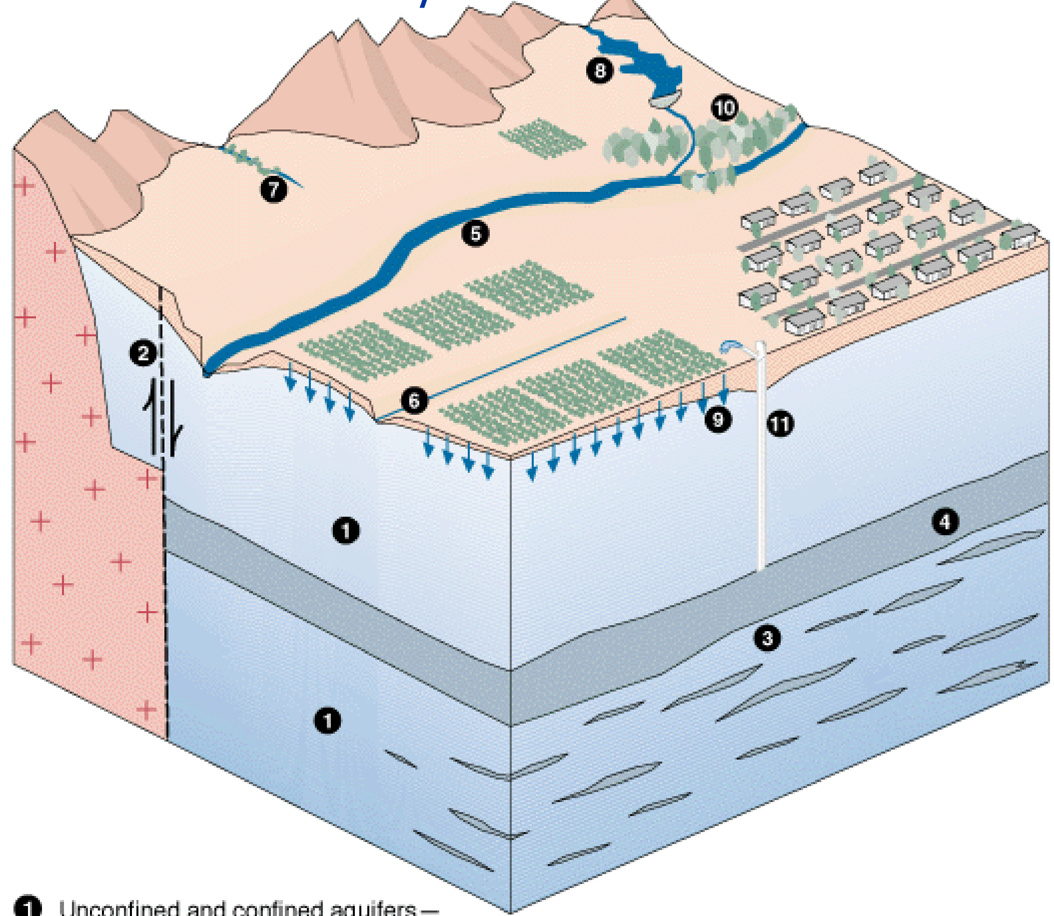

1. Unconfined and confined aquifers—Ground-water flow and storage changes
2. Faults and other barriers—Resistance to horizontal ground-water flow
3. Fine-grained confining units and interbeds
4. Confining units—Ground-water flow and storage changes
5. Rivers—Exchange of water with aquifers
6. Drains and springs—Discharge of water from aquifers
7. Ephemeral streams—Exchange of water with aquifers
8. Reservoirs—Exchange of water with aquifers
9. Recharge from precipitation and irrigation
10. Evapotranspiration
11. Wells—Withdrawal or recharge at specified rates

Simulation of Conjunctive Use Components

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Two types of Interdependency ➔ head-dependent flows and flow-dependent flows

➢<u>Indirect</u> ➔ Transfer of Flow in one Process/Package indirectly affects flows in another through the simulation of Groundwater Flow & Heads in Groundwater Flow Process (GWF) ➔ *original MODFLOW!!!*

➢<u>Direct</u> ➔ Transfer of Flows from one Process/Package to another

Types of other Processes that control Use & Flows:

<u>Landscape</u> ➔ Farm Process (FMP), Riparian-ET (RIP-ET)

<u>Surface-water</u> ➔ Streamflow Routing (SFR), Surface-Water Routing (SWR), Lake Package (LAK)

<u>Subsurface</u> ➔ Subsidence (SUB, SWT), Unsaturated Flow (UZF), Conduit-Flow (CFP), Multi-Node Wells (MNW1, MNW2), Groundwater Management (GWM)

Schematic representation of root zone and land surface flow processes simulated by MF-FMP

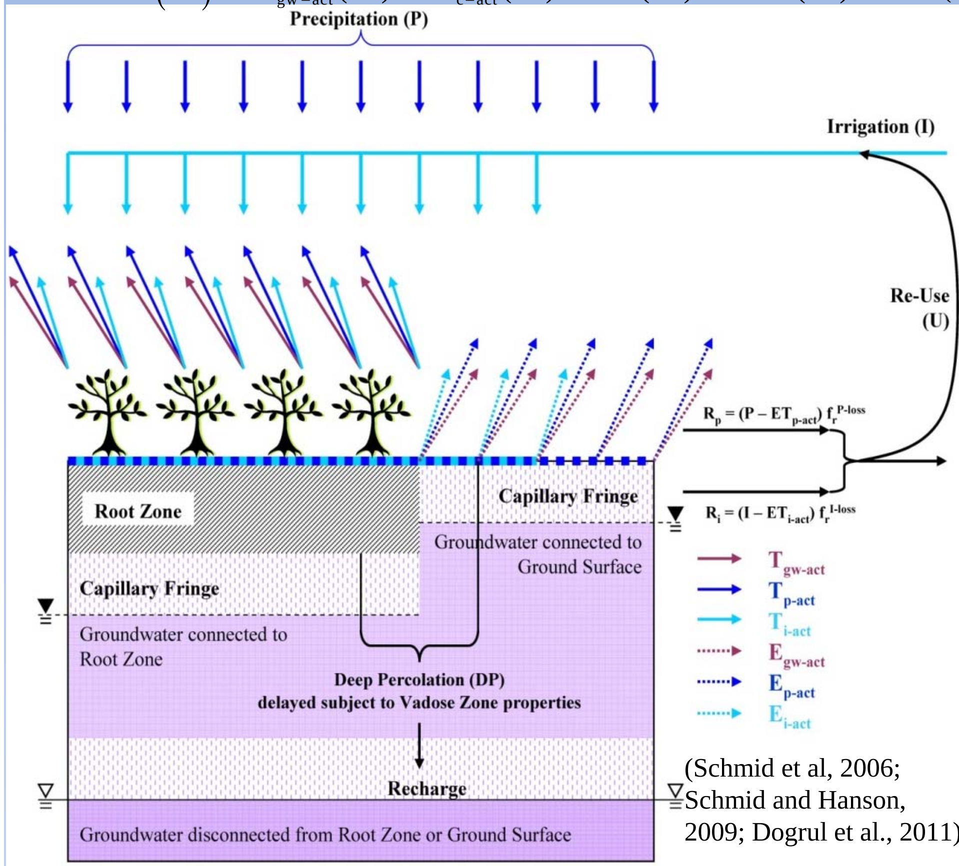
Evaporation from Direct uptake of Groundwater ➔

$$E_{gw-act} = \begin{cases} E_{i-pot} - E_{p-act} & \text{if } h \ge g \\ \left(E_{i-pot} - E_{p-act}\right)\left(1 - \frac{g+h}{c}\right) & \text{if } g < h < h_{ex}, \quad \text{with: } h_{ex} = g - c \\ 0 & \text{if } h \le h_{ex} \end{cases}$$

Evaporation from Irrigation $E_{i\text{-}act} = T_{i\text{-}act}\,(K_e^i/K_t)$

MF-FMP does not consider changes in soil water storage in the root zone (RHS in eqn 1 = 0) but does simulate changes in storage in the deeper vadose zone below the root zone through a linkage to UZF Pkg:

$$P^{k+1} + I^{k+1}\left(h^k\right) + ET^{k+1}_{gw-act}(h^k) - ET^{k+1}_{c-act}(h^k) - R^{k+1}(h^k) - DP^{k+1}(h^k) = 0 \qquad (1)$$



(Schmid et al, 2006; Schmid and Hanson, 2009; Dogrul et al., 2011)

$$T_{c-act} = \begin{cases} 0 & \text{if } h \ge h_{ux} \\ T_{c-pot}\dfrac{h_{ux} - h}{r} & \text{if } h_{ux} > h > h_{rb}, \quad \text{with}: h_{ux} = g - a \\ T_{c-pot}\left(1 - \dfrac{a}{r}\right) = T_{c=act\text{-}max} & \text{if } h \le h_{rb} \end{cases} \qquad (2)$$

$$T_{gw-act} = \begin{cases} 0 & \text{if } h \ge h_{ux} \\ T_{c-pot}\dfrac{h_{ux} - h}{r} & \text{if } h_{ux} > h > h_{wx}, \text{ with}: h_{ux} = g - a, \;\; h_{wx} = g - r + w \\ T_{c-pot}\left(1 - \dfrac{a+w}{r}\right) = T_{gw-act-max} & \text{if } h_{wx} \ge h > h_{rb} \\ T_{gw-act-max}\left(1 - \dfrac{h_{rb} - h}{d}\right) & \text{if } h_{lx} < h \le h_{rb}, \quad \text{with}: h_{lx} = g - r - d \\ 0 & \text{if } h \le h_{lx} \end{cases} \qquad (3)$$

$$T_{p-act} = \begin{cases} 0 & \text{if } h \ge h_{wx}, \text{ with}: h_{wx} = g - r + w \\ T_{c-act} - T_{gw-act} & \text{if } h < h_{wx}, \; T_{p-pot} > T_{c-act} - T_{gw-act} \\ T_{p-pot} & \text{if } h < h_{wx}, \; T_{p-pot} \le T_{c-act} - T_{gw-act} \end{cases} \qquad (4)$$

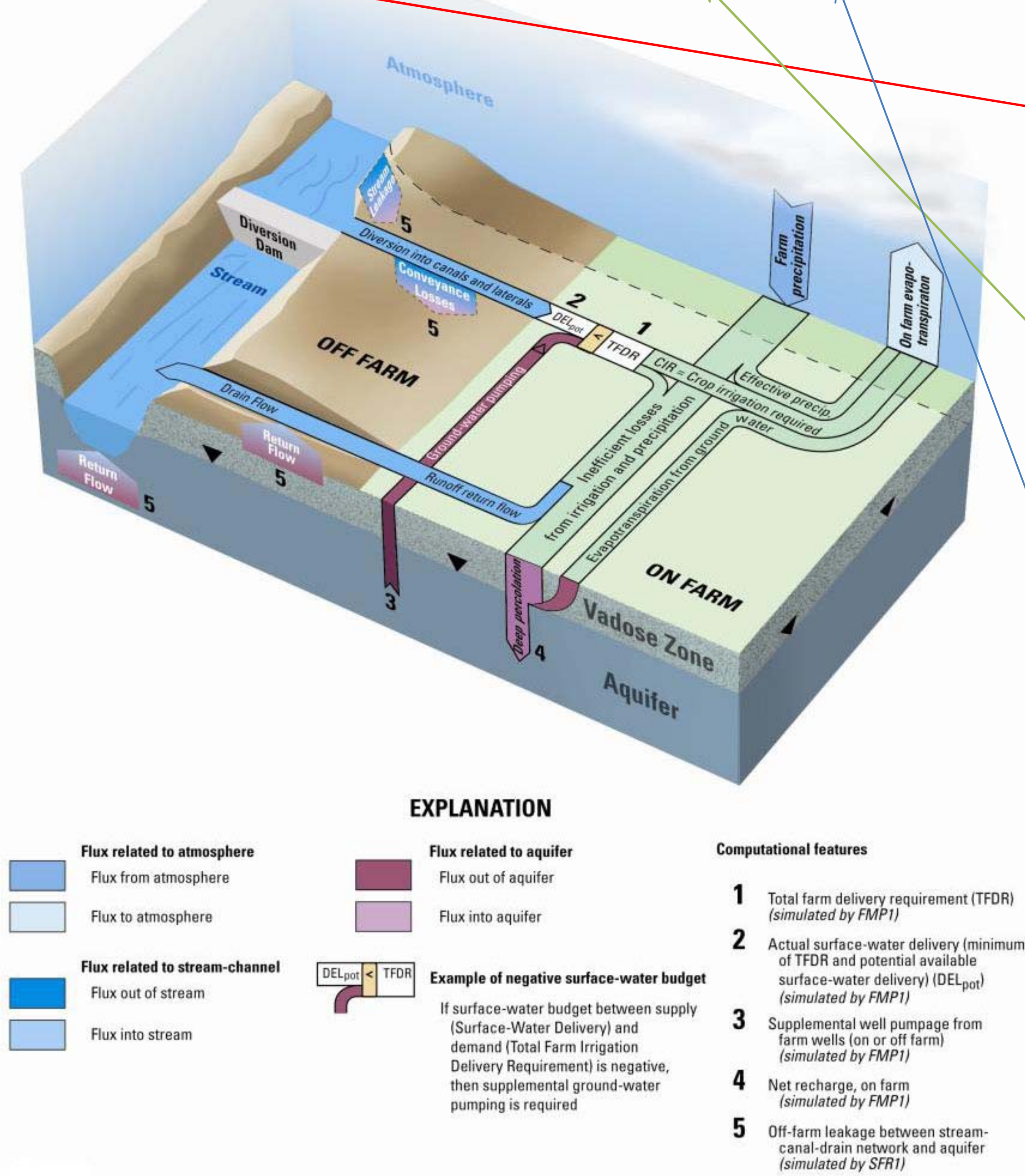
$T_{i\text{-}act} = T_{c\text{-}act} - T_{gw\text{-}act} - T_{p\text{-}act}$

a = depth of the anoxia fringe (L), w = depth of wilting zone (L).
r = total depth of root zone (L), d = depth of capillary fringe (L),
g = ground-surface elevation (L), h = groundwater head elevation (L),
h_{rb} = groundwater head elevation at the bottom of the root zone (L),
h_{ux} = head elevation where top of anoxia fringe, a, above the water level is at ground-surface elevation, g (*elevation of upper transpiration extinction*) (L),
h_{wx} = head elevation at which bottom of the wilting zone, w, is at ground-surface elevation, g (*elevation of wilting zone extinction*) (L),
h_{lx} = head elevation at which top of capillary fringe, d, is at bottom of root zone, h_{rb} (*elevation of lower transpiration extinction*) (L).

For 'Concept 1,' $T_{c\text{-}act}$ varies linearly (eq. 2) between elevation of upper transpiration extinction, h_{ux}, and the elevation of the root-zone bottom, h_{rb}. For heads below the root-zone bottom, $T_{c\text{-}act}$ is constant and reduced by the ratio between the anoxia fringe, a, and the total root zone, r. In eq. (3), $T_{gw\text{-}act}$ varies linearly between the elevation of upper transpiration extinction, h_{ux}, and the elevation of wilting zone extinction, h_{wx}. For heads between h_{wx} and root-zone bottom, $T_{gw\text{-}act}$ is constant and reduced from $T_{c\text{-}pot}$ to a maximum actual transpiration from groundwater, $T_{gw\text{-}act\text{-}max}$, by the ratio between the sum of anoxia and wilting zones, a + w, and the total root zone, r. $T_{gw\text{-}act}$ also varies linearly between the head elevations between the root-zone bottom and lower transpiration extinction, h_{lx}. In eq. (4), $T_{p\text{-}act}$ is equal to $T_{p\text{-}pot}$, except when limited to the remainder of $T_{c\text{-}act}$ that is not yet satisfied by transpiration fed by $T_{gw\text{-}act}$.

For 'Concept 2,' wilting and anoxia above the water level are not simulated (a & w = 0 in eqs. (2) & (3)), but $T_{c\text{-}pot}$ is still linearly reduced to $T_{c\text{-}act}$ (eq. (2)) or $T_{gw\text{-}act}$ (eq. (3)) as the active root zone is reduced by a rising water level. $T_{c\text{-}act}$ equals $T_{c\text{-}pot}$ for water levels below the root-zone bottom and $T_{gw\text{-}act}$ reaches $T_{c\text{-}pot}$ for water levels located at the root-zone bottom.

$$P^{k+1} + I^{k+1}\left(h^k\right) + ET^{k+1}_{gw-act}(h^k) - ET^{k+1}_{c-act}(h^k) - R^{k+1}(h^k) - DP^{k+1}(h^k) = 0 \qquad (1)$$



Irrigation: MF-FMP computes I as the portion of actual transpiration and evaporation (7) after potential input from groundwater and then precipitation and divided by the crop irrigation efficiceincy for that farm/crop:

$$CIR = ET_{i\text{-}act} = T_{i\text{-}act} + E_{i\text{-}act} \Rightarrow I^{t,k+1} = \frac{ET^{t,k+1}_{i-act}(h^{t,k})}{e^t} \qquad (7)$$

Runoff: MF-FMP computes R as the portion of crop-inefficient losses from precipitation (5) or irrigation (6) that contribute to runoff/returnflow:

$$R_p = (P - ET_{p-act}) f_r^{P-loss} \qquad (5)$$

$$R_i = (I - ET_{i-act}) f_r^{I-loss} \qquad (6)$$

Deep Percolation: MF-FMP computes DP as the sum of deep percolation below the root zone from precipitation and irrigation (8). It is the user-specified portion of losses of precipitation and irrigation that are not consumptively used by plants and not lost to surface water runoff:

$$DP = (P - ET_{p-act})\left(1 - f_r^{P-loss}\right) + (I - ET_{i-act})\left(1 - f_r^{I-loss}\right) \qquad (8)$$

USGS MODLOW with the FARM PROCESS—Features and Capabilities

Supply-and-Demand Modeling Framework Connected to Nature and Humanity

Farm Demand for Irrigation

Non-Routed Deliveries as Water Transfers

Routed Surface-Water Delivery to Farm

Groundwater Pumpage by Well

Streamflow Conveyance and Drain Network

Natural and Artificial Recharge

Water-Use Management

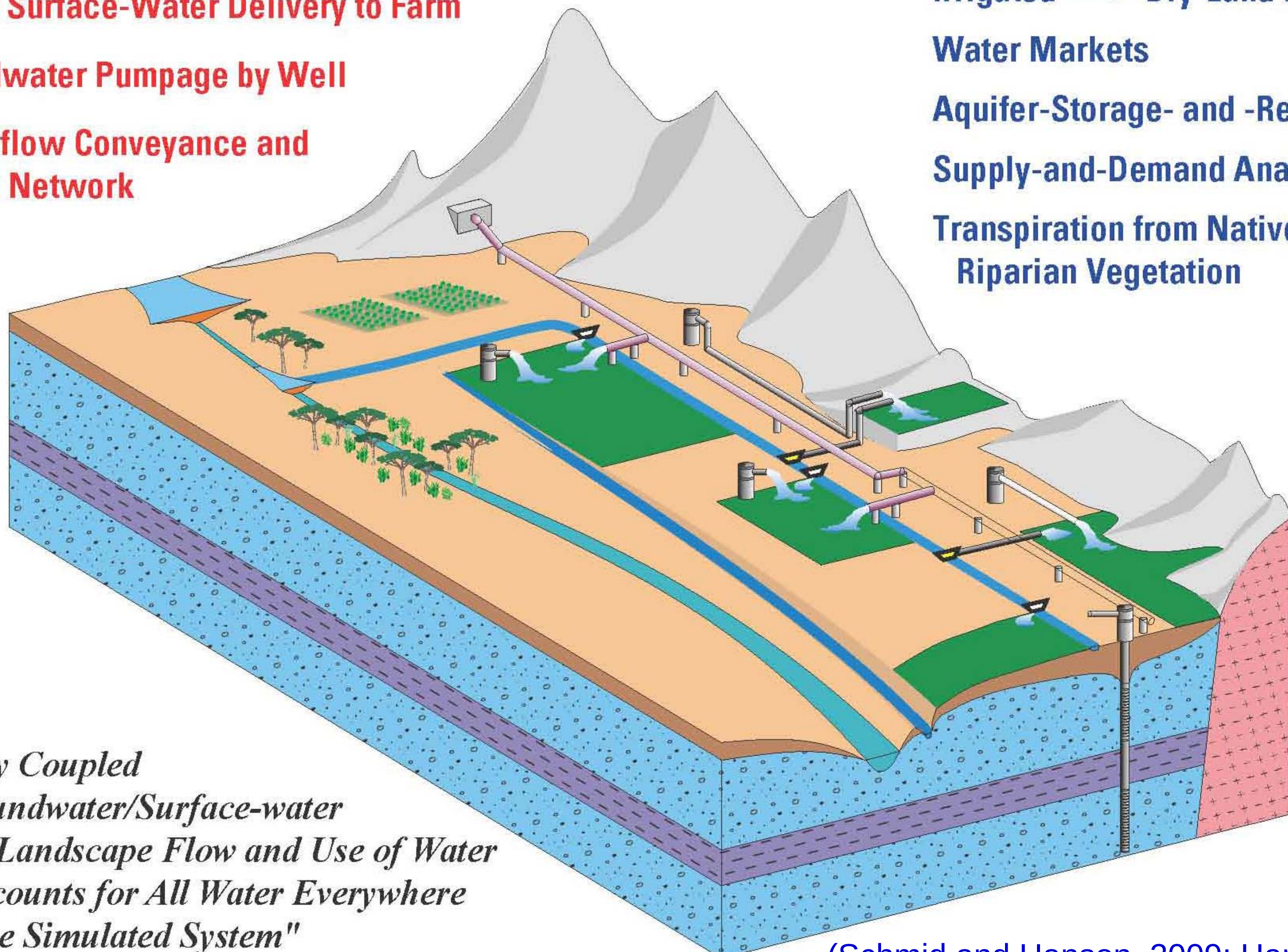
Irrigated ⟹ Dry-Land Farming

Water Markets

Aquifer-Storage- and -Recovery Systems

Supply-and-Demand Analysis

Transpiration from Native and Riparian Vegetation



Fully Coupled Groundwater/Surface-water and Landscape Flow and Use of Water "Accounts for All Water Everywhere in the Simulated System"

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(Schmid and Hanson, 2009; Hanson et al., 2010)

Theory of FMP

Why do we need a “Farm Process?”

What is the Usefulness

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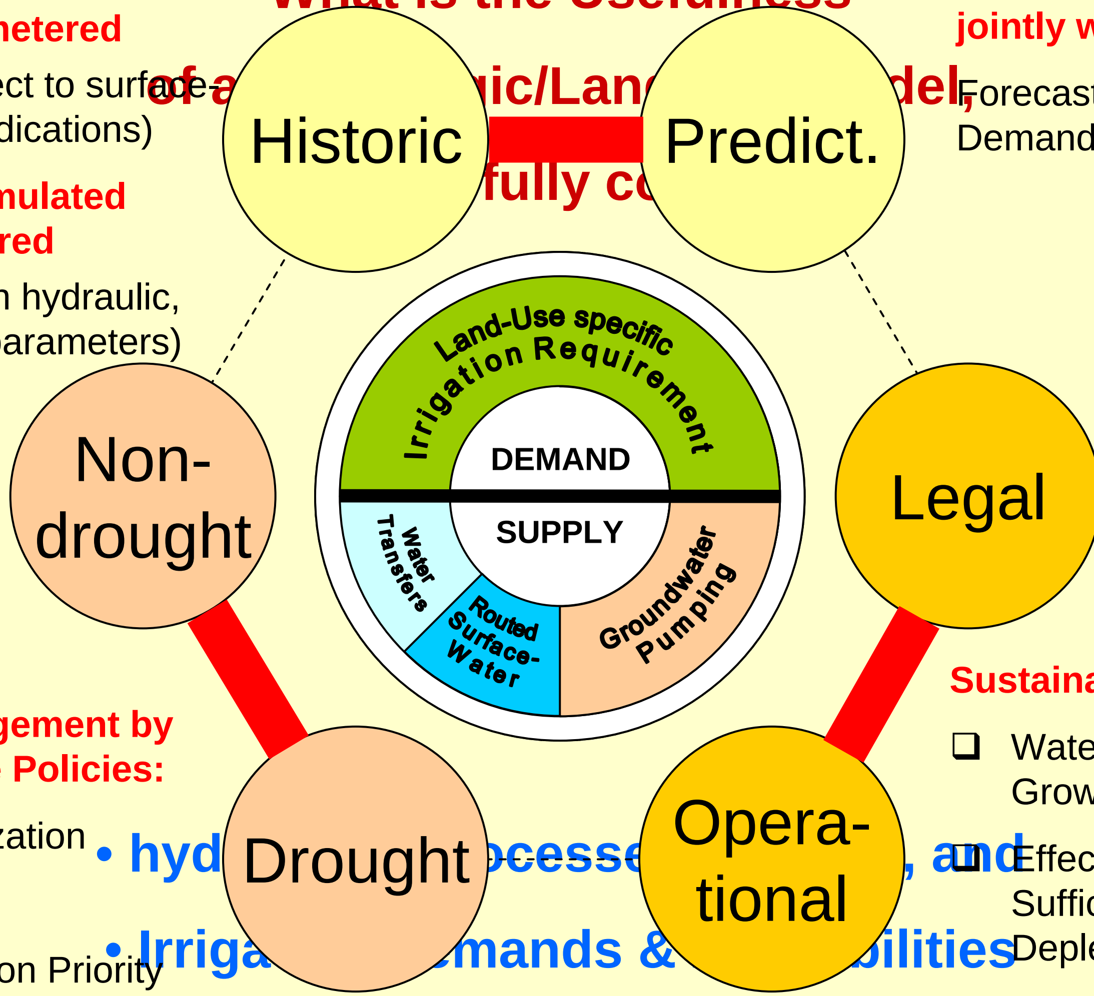

Estimation of Historic Well Pumpage if not metered

(e.g., if wells subject to surface-water stream adjudications)

Calibration of Simulated Pumpage if metered

(estimate unknown hydraulic, land-use, & farm parameters)

Climate Model Predictions jointly with Farm Package

Forecast of Future Supply & Demand (e.g. ahead of Droughts)

Surface-Water Rights Appropriations

- ❑ Individual “Farms”;
- ❑ Irrigation Districts;
- ❑ Transboundary Set.

Conjunctive Management by Drought Response Policies:

- ❑ Acreage Optimization
- ❑ Deficit Irrigation
- ❑ Water-Stacking on Priority Crops

Sustainable Management:

- ❑ Water Allocations Prior to Growing Season;
- ❑ Effects of Water-Transfers on Sufficiency or Recovery of Depleted Aquifers;
- ❑ Effects of Natural and Artifical Recharge on Depleted Aquifers.

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• Irriga... emands & ... bilities

• on a Farm by Farm Accounting Basis?

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Features, Capabilities, Advantages

MODEL ESTIMATION FEATURES

Irrigation Demand
Surface-Water Deliveries
Ground-water Pumpage
Net Recharge
ET, Runoff, & Deep Percolation
Complete Linkage to Groundwater and Surface-water Flow

CAPABILITIES

Supply-and-Demand Analysis for Historical and Future Land Use & SW/GW conjunctive Water-Use Management
- **Natural**
- **Agricultural (Irrigated & Dry-Land Farming)**
- **Urban**

Analysis of optimal, improved, or alternative water use subject to
- **Insufficient Supply (drought conditions)**
- **Climate changes and Climate change adaptation**

Aquifer-Storage-and-Recovery Systems:
- **Storage in times or regions of higher abundance and release during peak demand**

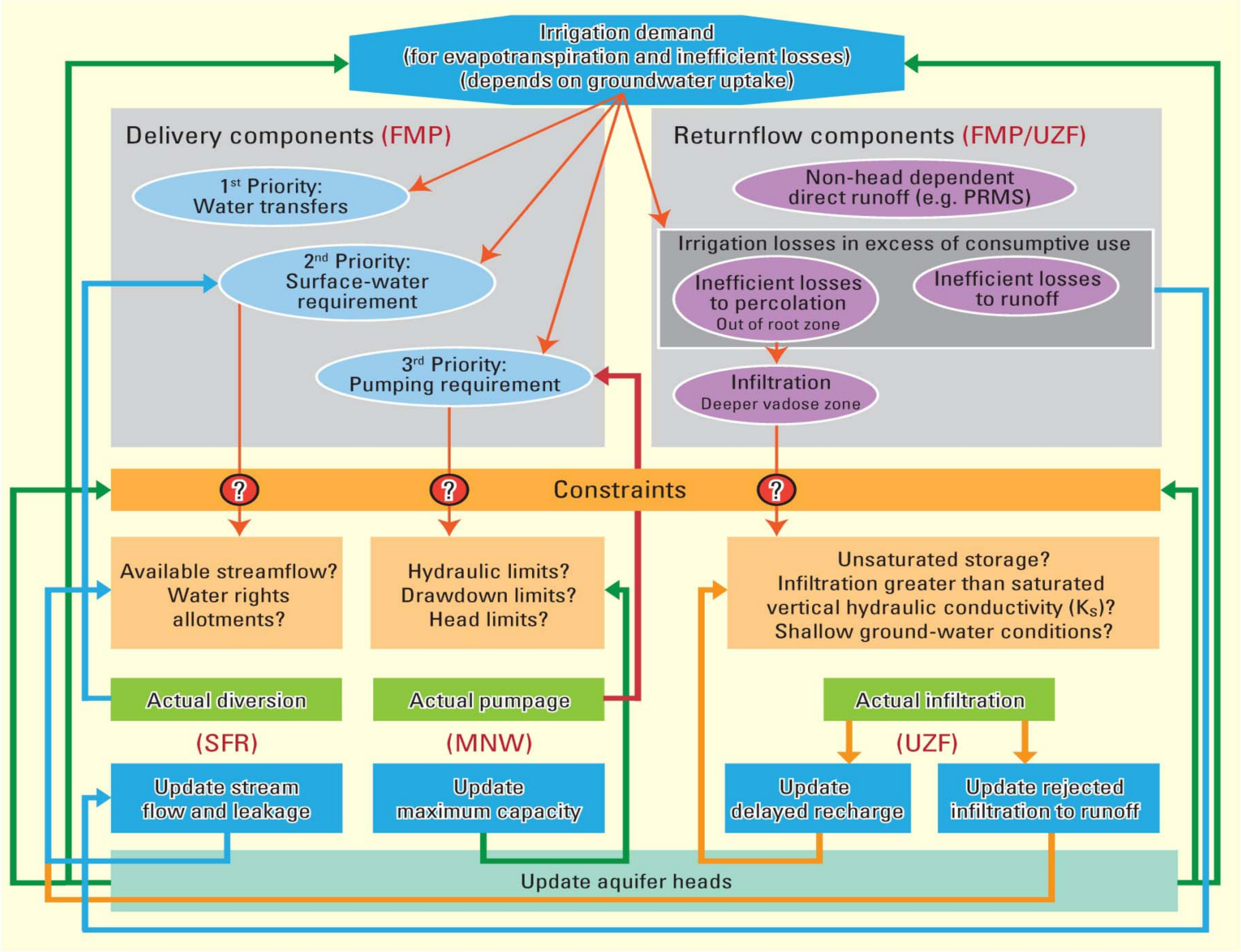
Water markets between
- **wetter supply regions and**
- **drier demand regions**

ADVANTAGES FOR MODELERS & WATER MANAGERS

No need for separate indirect estimates of Pumpage, Recharge, ET, Runoff, or Surface-water deliveries
Uses Natural Data ➔ Easy to Update Model
Easy to Analyze Flows and Movement of Water
Saves time & money for constructing, operating, & updating models
Facilitates Operational and Forecasting Simulations

Current Features of MF2005-FMP2

- Demand and Supply (Demand-Driven/Supply-Constrained)
- Demand Drivers (ET, ASR-Wellfields)
- Resource Constraints (Surface-Water Rights, max. GW pumping capacities, Surface-Water/Groundwater Allotments)
- Return Flows (Natural and Irrigation Returnflows -- Runoff, Percolation / Recharge)
- Drought Scenarios/ Conjunctive Use/ Sustainability Analysis



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Farm Process (FMP)
Multi-Node Well Package (MNW)
Streamflow Routing Package (SFR)
Unsaturated-Zone Flow Package (UZF)
Inflow constraints

Features of MF2005-FMP2

- Calculation of Farm Irrigation Demand after taking into account
  - consumption of available precipitation and GW root uptake
  - in-efficient losses
- Simulation of Water Supply Components in following sequence
  - water transfers (imported water, deliveries from well fields, ASR recovery wells)
  - surface-water routed via conveyance network
  - groundwater pumpage
- Simulation of Surface-Water Supply according to Water Rights Schemes
  - equal appropriation (correlative water right)
  - prior appropriation with or without maximum allotment
- Estimation of Percolation (instant and delayed Recharge) and Return Flow
- Calculation of several Mass Balances
  - Groundwater Budget (+ Farm Wells & Net Recharge) for entire Domain or for Zones
  - Farm Budget of all Mass Inflows and Outflows
  - Farm Demand and Supply Budget
- Adjustment of Out-of-Balance Demand and Supply
  - drought scenarios (for deficiency) or recharge options (for excess supplies)

Features of MF2005-FMP2

- **Crop coefficients and reference evapotranspiration**
  - crop specific crop coefficients (K_c) available in literature databases (e.g., FAO 56);
  - regional reference evapotranspiration (ET_r) data available (e.g., California Irrigation Management Information System, CIMIS);
  - FMP calculates product: $ET_{c\text{-}pot} = K_c \times Et_r \Rightarrow ET_{act} = ET_{c\text{-}pot} * FTR$
- **Root uptake under variable saturated conditions**
  - for certain crops and riparian vegetation (e.g., rice and willow trees) that do not reduce uptake as a result of anoxic conditions in the unsaturated zone;
  - reduction of uptake as positive pressure heads increase in the saturated root zone.
- **Simulation of non-irrigation conditions for non-irrigated vegetation.**
  - Not calculated: irrigation requirement or excess irrigation return flows;
  - Still calculated: transpiration & evaporation portions fed by precipitation & groundwater, and runoff-return flows & deep percolation from excess precipitation.
- **Matrix of on-farm efficiencies by farm AND by crop type.**

Features of MF2005-FMP2

- Improved surface-water "plumbing" for deliveries & return flows
  - in addition to fully routed runoff return flow, new option to specify locations (reaches) along the stream network, where runoff should be return to.
  - deliveries only from <u>diversion segments</u> & return flows only to <u>non-diversion segments</u> or deliveries from <u>any type of segment</u> and return flows to <u>any type of segment.</u>
- Pumping of wells restricted in areas with no crop irrigation requirement
- Delayed recharge and rejected runoff by link to UZF package
  - FMP-simulated percolation beyond root zone treated as UZF-infiltration into vadose zone;
  - Simulation of delayed recharge beneath farms and/or virtual farms (e.g., ASRs);
  - Simulation of runoff from infiltration in excess saturated hydraulic conductivity;
  - Simulation of runoff from rejected runoff and groundwater discharge to land surface;
  - Correction of FMP percolation and runoff by the above runoff components.

  → Linkage between UFZ and FMP yields delayed recharge, various runoff components, and delayed recovery.

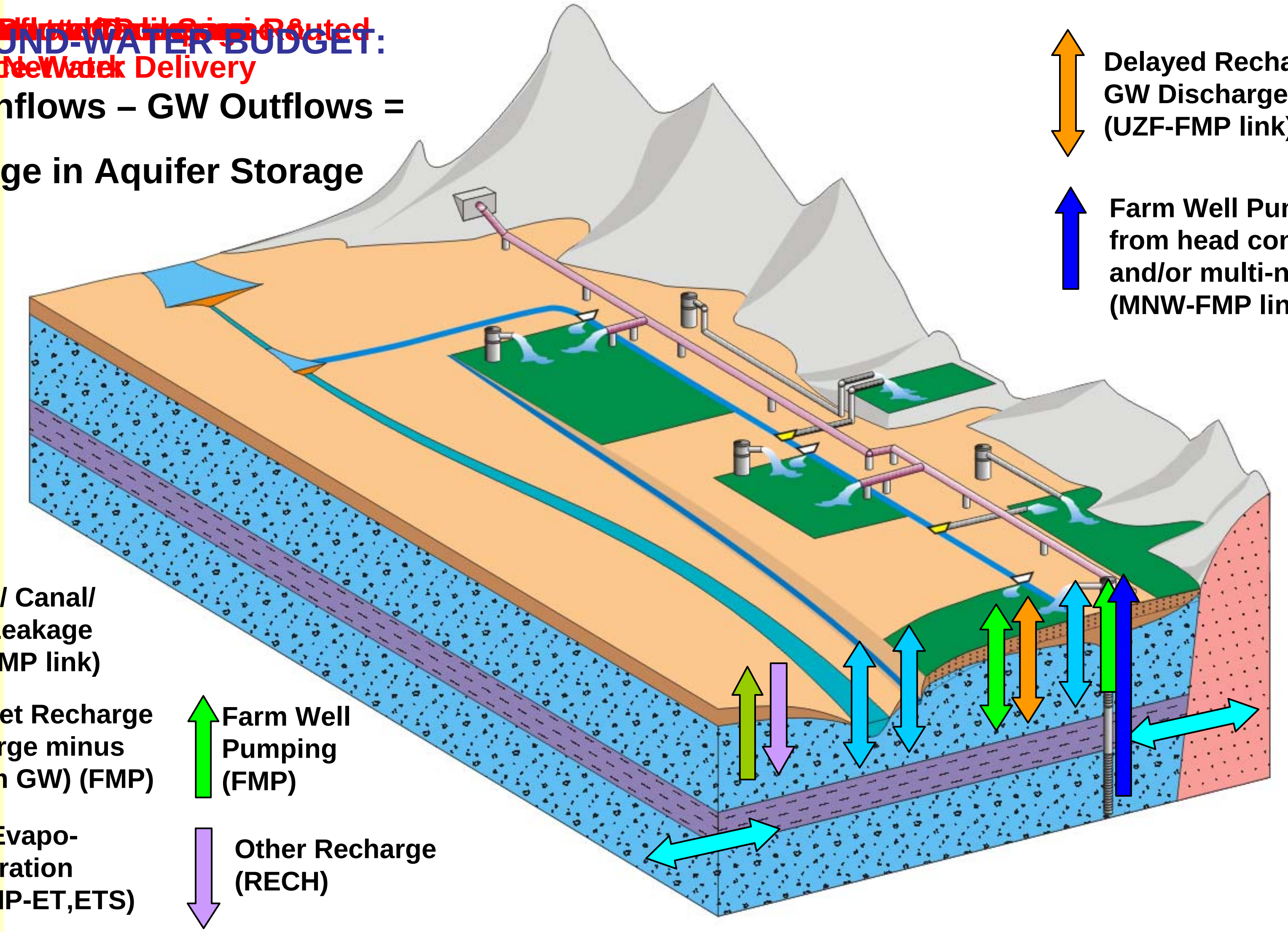
Features of FMP2

Demand & Supply
Mass Balance

GROUND-WATER BUDGET:

GW Inflows – GW Outflows =

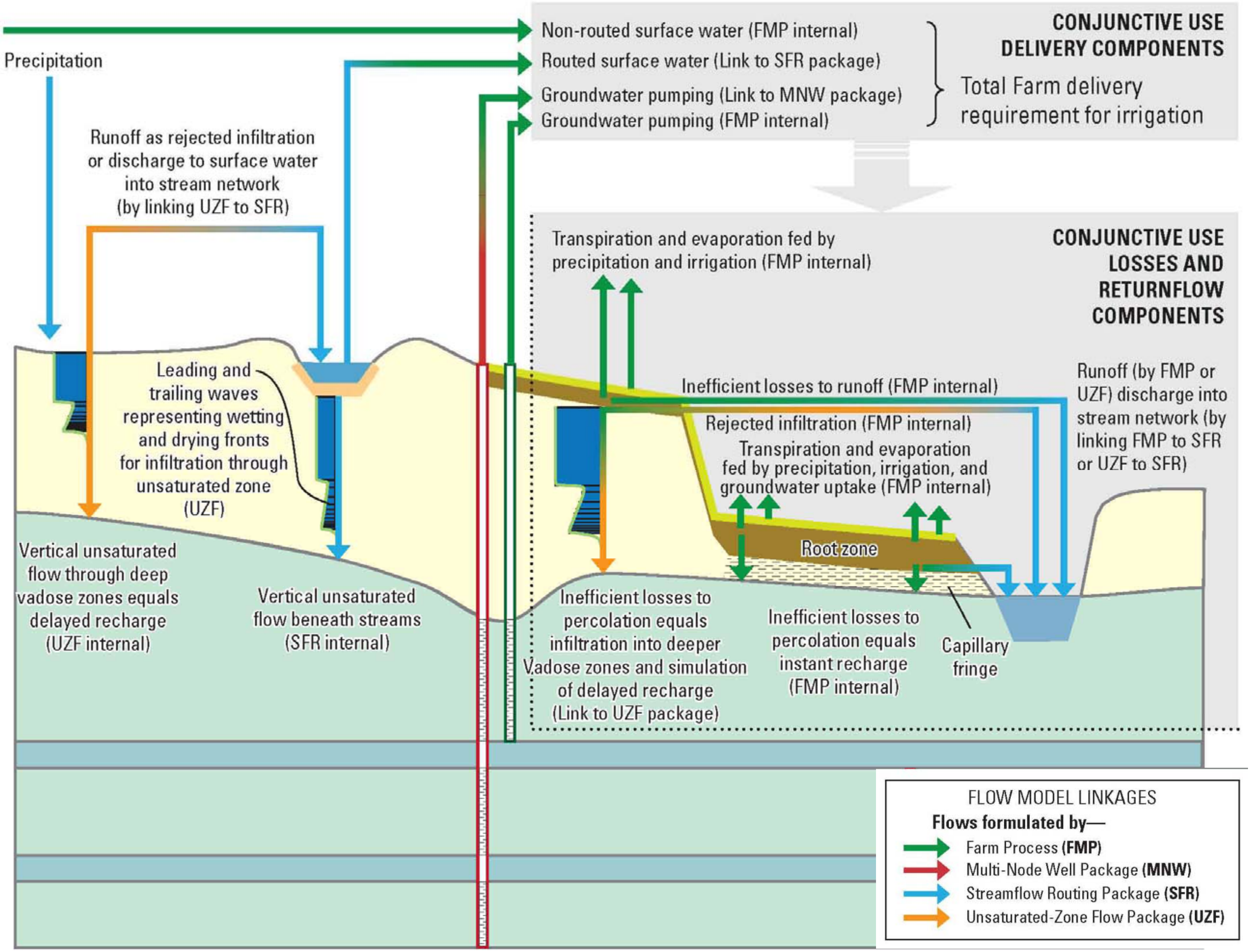
Change in Aquifer Storage



- **Delayed Recharge and GW Discharge to Surface (UZF-FMP link)**
- **Farm Well Pumping from head constrained and/or multi-node wells (MNW-FMP link)**
- **Stream/ Canal/ Drain Leakage (SFR-FMP link)**
- **Farm Net Recharge (Recharge minus ET from GW) (FMP)**
- **Farm Well Pumping (FMP)**
- **Other Evapo-transpiration (EVT,RIP-ET,ETS)**
- **Other Recharge (RECH)**
- **Boundary In- and Outflows (CHB, GHB, etc)**

Features of FMP2

Linked Mass Flows

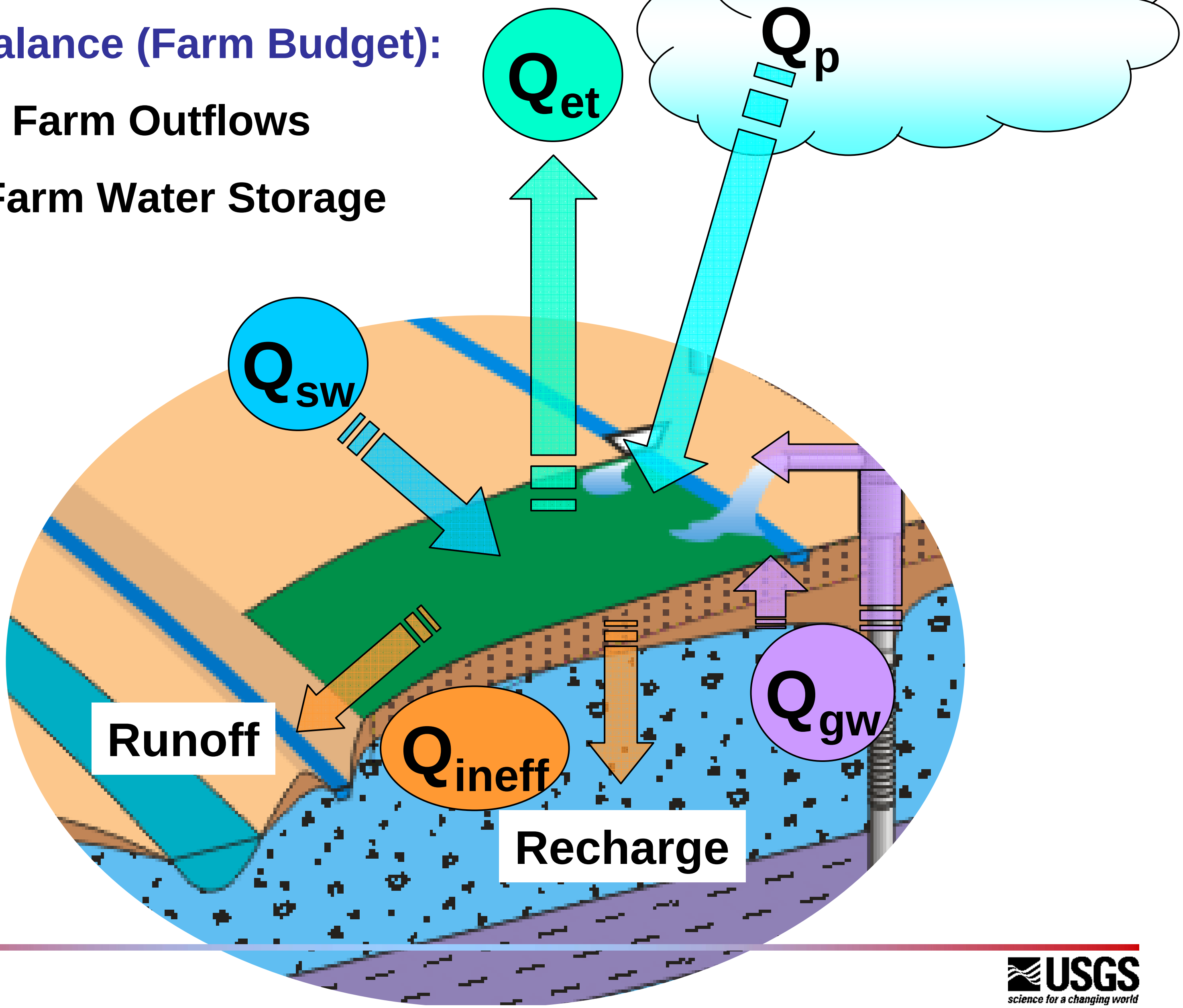


Features of FMP2

Farm Mass Balance (Farm Budget):

Farm Inflow – Farm Outflows

= Change in Farm Water Storage



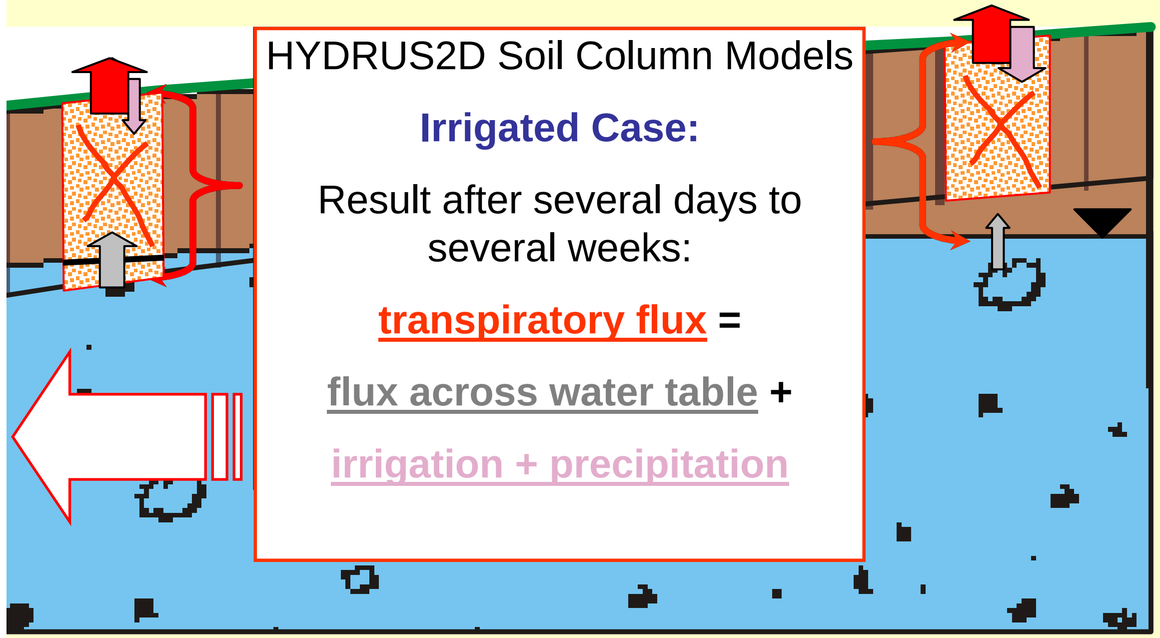
for time steps commonly used with MODFLOW:

changes in soil water storage in the root zone neglected in Farm Process

$q_{et}(h) = q_{et\text{-}gw}(h) + q_{et\text{-}i} + q_{et\text{-}p}$

$q_{et\text{-}i}(h) =$

$q_{et}(h) - q_{et\text{-}p} - q_{et\text{-}gw}(h)$



HYDRUS2D Soil Column Models

Irrigated Case:

Result after several days to several weeks:

transpiratory flux =

flux across water table +

irrigation + precipitation

Changing parameter		Impact on	Method
Water level		- active root zone (q_t, $q_{t\text{-}gw}$) - transpiration extinction ($q_{t\text{-}gw}$) - evaporation extinction ($q_{e\text{-}gw}$)	Linear approximations verified by HYDRUS2D results
Anoxia depth	Crop type Soil type Root Zone Depth Capillary Fringe Potential Transp.	- active root zone (q_t, $q_{t\text{-}gw}$)	Analytical Solutions verified by HYDRUS2D results
Wilting depth		- active root zone ($q_{t\text{-}gw}$)	

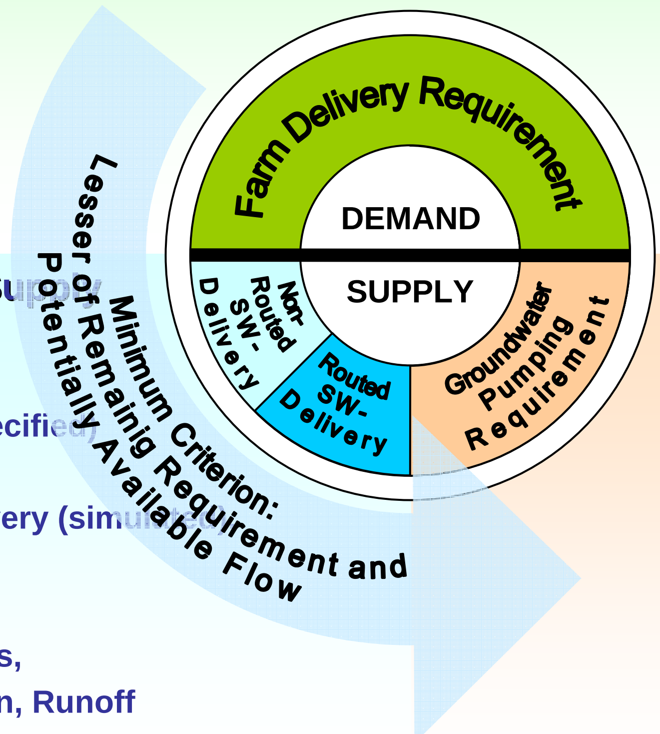
Features of FMP

FMP checks if Farm Demand can be met by Supply Components

Step 1: Irrigation Demand

Total Farm Delivery Requirement, depends on:

- Crop Evapotranspiration (Climate, Aquifer), Effective Precipitation (Climate)
- Uptake from Groundwater (Aquifer head)
- On-Farm Efficiency, OFE, (Management)



Step 2: Surface-Water Supply

Non-Routed or Imported
Surface-Water Delivery (specified)
and
Routed Surface-Water Delivery (simulated)
depends on:

- Stream Flow
  - Release, Diversions,
  - Stream-Evaporation, Runoff
  - Conveyance Losses (Aquifer head)
- Water Rights Constraints

Step 3: Groundwater Pumping

Limited by maximum farm-well capacities

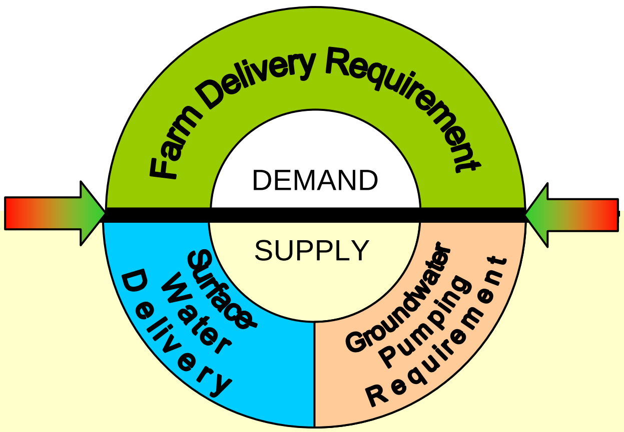
- as specified for the FMP;
- as simulated by the link between FMP and MNW1 package.

Features of FMP

Adjustment of "Out-of-Balance" Farm Demand & Supply Budget

What if Irrigation Requirement does not match the actual Irrigation Supply ?

Irrigation Deficiency: $Q_{i\text{-}req} > Q_i$



Application of Drought Policies in FMP

- **Deficit Irrigation;**
- **"Water Stacking" onto Priority Crops;**
- **Optimization of agricultural profit against irrigated acreage;**
- **"Zero Scenario:" Demand supplemented by outside Sources.**

Irrigation Surplus of Nonrouted Deliveries: $Q_{i\text{-}req} < Q_i \rightarrow Q_{i\text{-}req} < Q_{nrd}$

- Inject Surplus into Farm Wells, or
- Recharge Surplus back into adjacent Canal

Allows "non-farm" water allocations (e.g. for Aquifer-Storage-and-Recovery)

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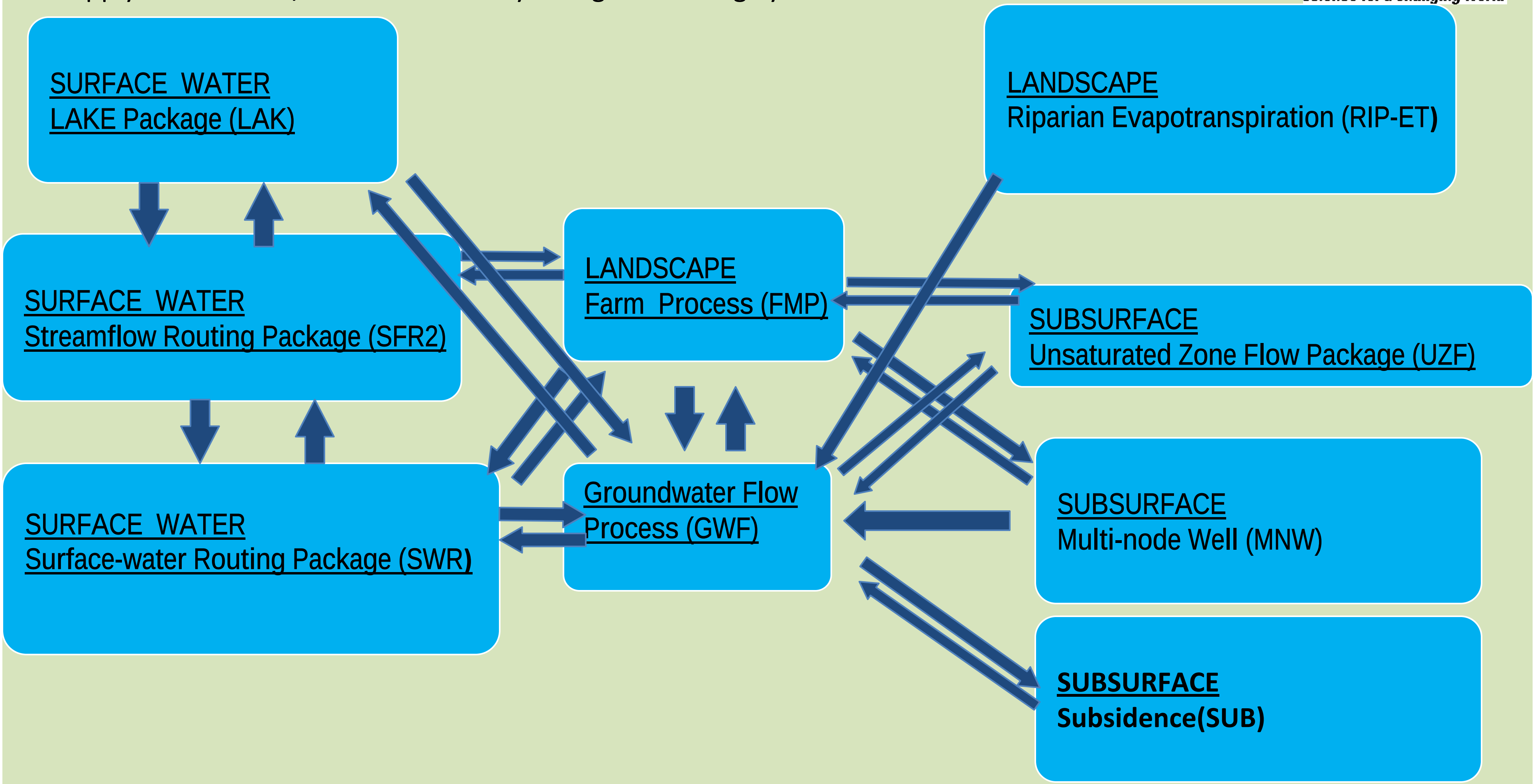
- Summary & Conclusions

MODFLOW-FMP CONJUNCTIVE-USE DEVELOPMENT

Supply-Constrained/Demand-Based Hydrologic Modeling System



Ongoing FMP Developments (soon to be released)

- Climate Change – Adaptation and Non-Adaptation Scenarios
- Linkage of FMP models to Regional or Global Climate Models
- Subsidence Linkage to Aquifer (LPF) & Surface Features (FMP, SFR, & SWR) ➔ Vertically deforming mesh & changes in Streamflow, Runoff, Etgw
- Physiologically-based Plant-Colony Riparian ET (RIP-ET)
- Local Grid Refinement ➔Parent and Child Models with FMP and SFR
- Changing Water-Balance Regions ➔ Changing Land-Use
- Groundwater Allotments ➔ Sustainability Analysis/Water Rights Assessment
- Variable Water-Accounting Subregions ➔ Changes in Land Use/Ownership & potential linkage to Land-use models

Ongoing MF-FMP Developments

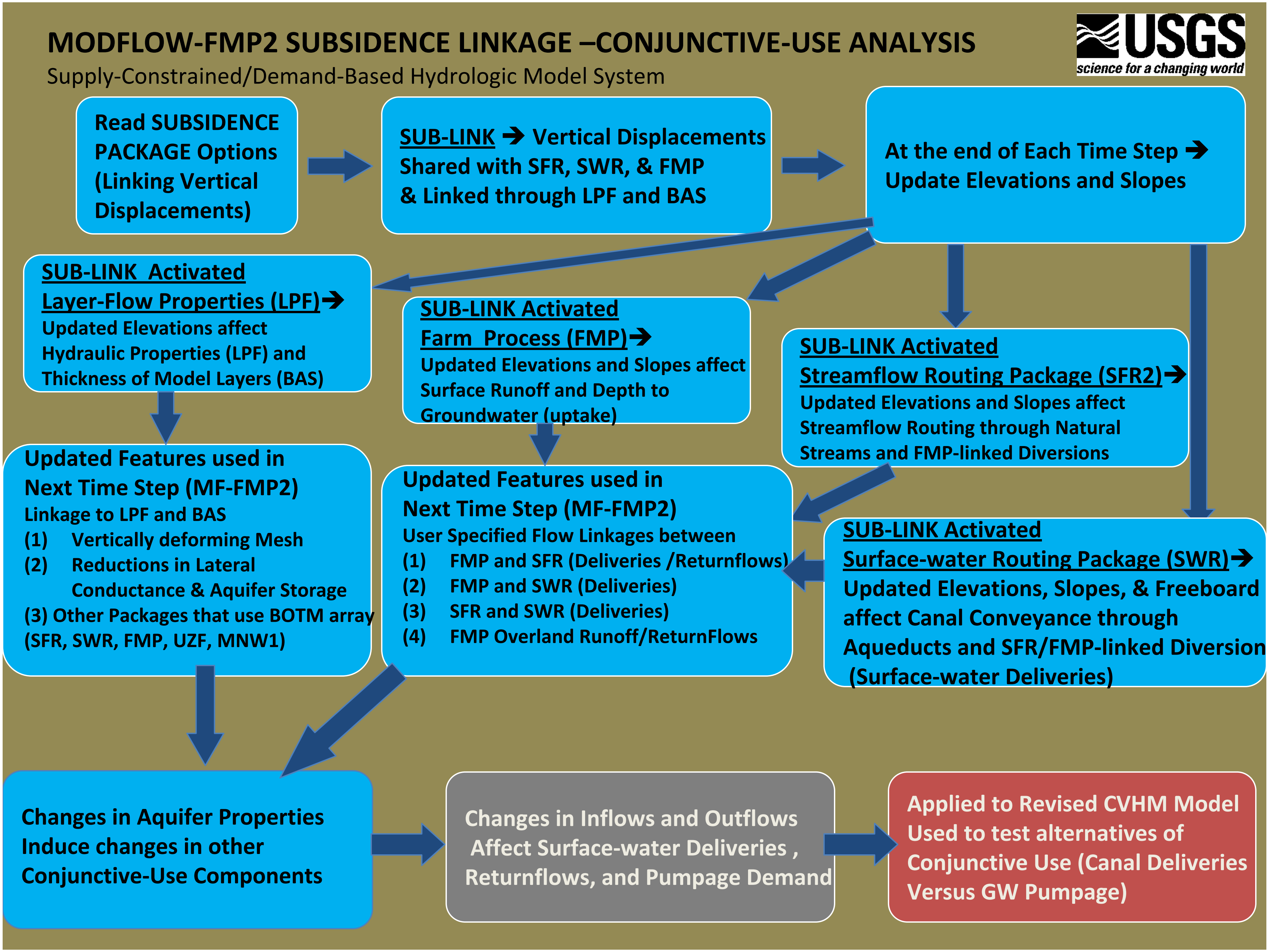
- Additional Types of Physical Flow Budgets

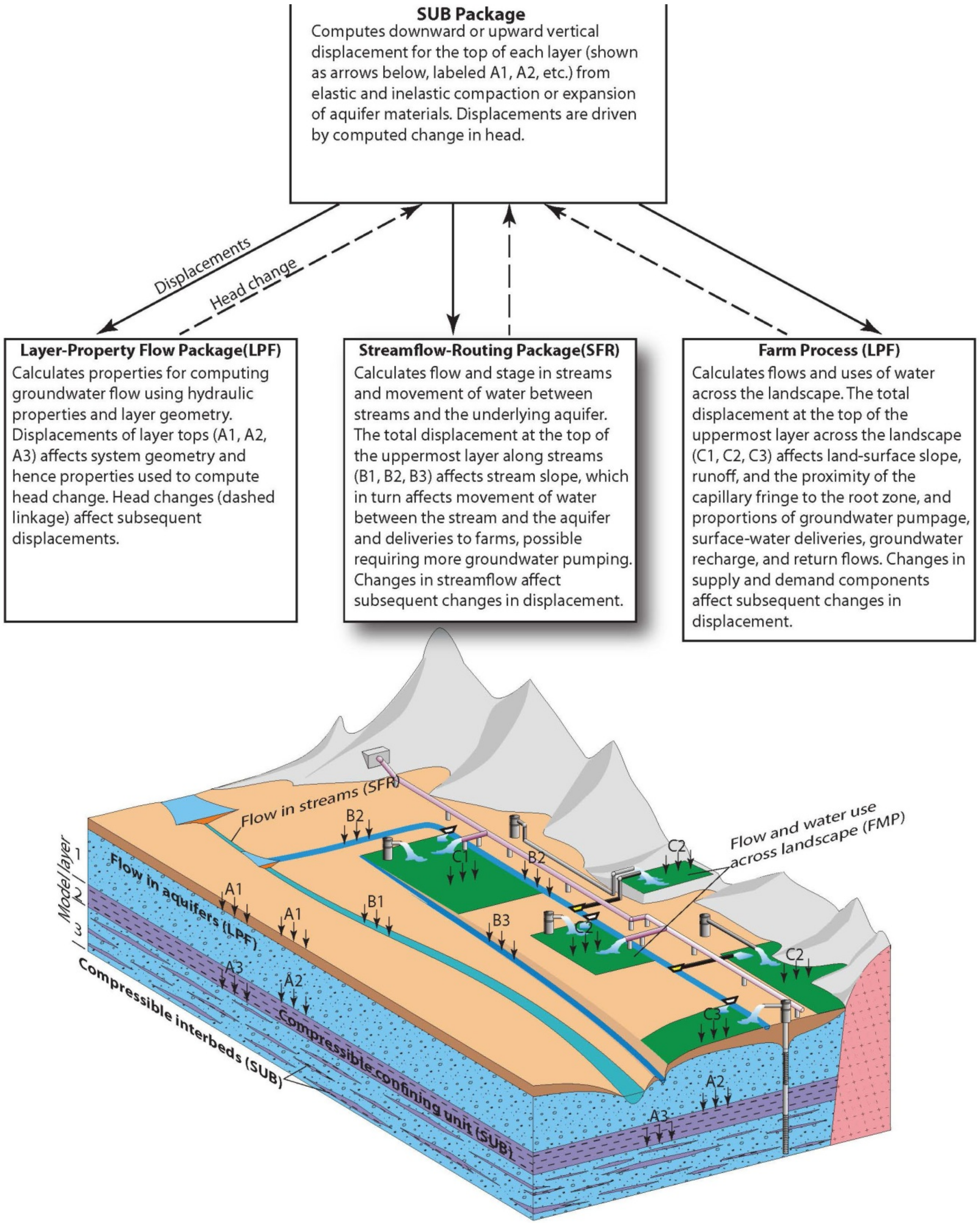
  - ET by crop type within each farm (sub-budgets of Farm Budget)
  - Separation of ET and Recharge in Groundwater Budget (or ZONEBUDGET) (already split in Farm Budget)

- Subsidence

  - Subsidence already jointly simulated with FMP Models by SUB Package
    - ➢ Central Valley Hydrologic Model

  - Feedback of vertical displacement to:
    - ➢ deforming mesh and hydraulic properties (LPF Package)
    - ➢ changes in ground-surface elevation affecting runoff and root uptake from Groundwater (FMP)
    - ➢ changes in streambed elevations and slopes affecting streamflow (SFR)


MODFLOW-FMP2 SUBSIDENCE LINKAGE –CONJUNCTIVE-USE ANALYSIS
Supply-Constrained/Demand-Based Hydrologic Model System
USGS science for a changing world
Read SUBSIDENCE PACKAGE Options (Linking Vertical Displacements)
SUB-LINK → Vertical Displacements Shared with SFR, SWR, & FMP & Linked through LPF and BAS
At the end of Each Time Step → Update Elevations and Slopes
SUB-LINK Activated Layer-Flow Properties (LPF) → Updated Elevations affect Hydraulic Properties (LPF) and Thickness of Model Layers (BAS)
SUB-LINK Activated Farm Process (FMP) → Updated Elevations and Slopes affect Surface Runoff and Depth to Groundwater (uptake)
SUB-LINK Activated Streamflow Routing Package (SFR2) → Updated Elevations and Slopes affect Streamflow Routing through Natural Streams and FMP-linked Diversions
Updated Features used in Next Time Step (MF-FMP2)
Linkage to LPF and BAS
(1) Vertically deforming Mesh
(2) Reductions in Lateral Conductance & Aquifer Storage
(3) Other Packages that use BOTM array (SFR, SWR, FMP, UZF, MNW1)
Updated Features used in Next Time Step (MF-FMP2)
User Specified Flow Linkages between
(1) FMP and SFR (Deliveries /Returnflows)
(2) FMP and SWR (Deliveries)
(3) SFR and SWR (Deliveries)
(4) FMP Overland Runoff/ReturnFlows
SUB-LINK Activated Surface-water Routing Package (SWR) → Updated Elevations, Slopes, & Freeboard affect Canal Conveyance through Aqueducts and SFR/FMP-linked Diversion (Surface-water Deliveries)
Changes in Aquifer Properties Induce changes in other Conjunctive-Use Components
Changes in Inflows and Outflows Affect Surface-water Deliveries, Returnflows, and Pumpage Demand
Applied to Revised CVHM Model Used to test alternatives of Conjunctive Use (Canal Deliveries Versus GW Pumpage)



Will also include displacements for Drain Package and NWT's UPW Package

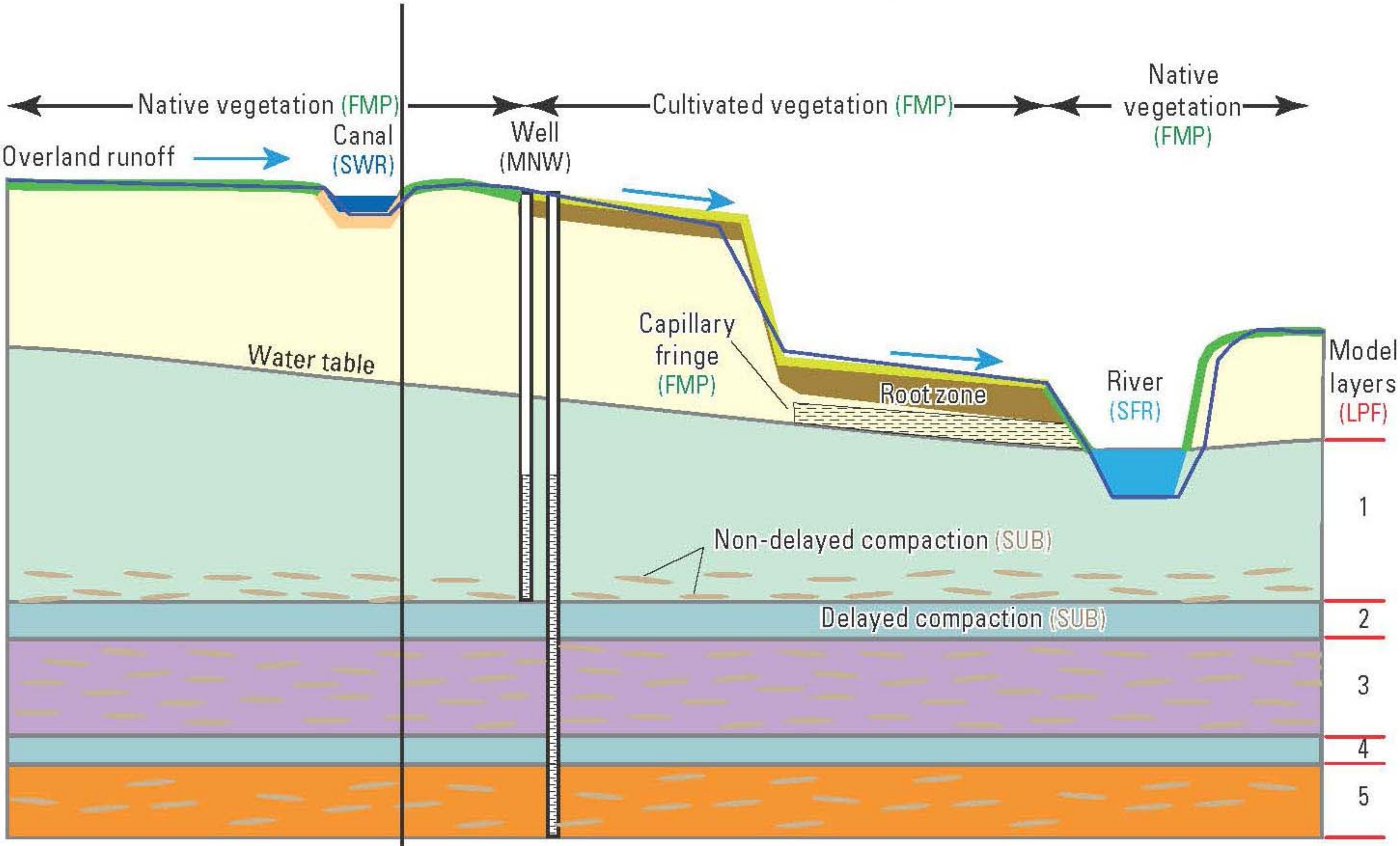
Before subsidence

Landscape processes

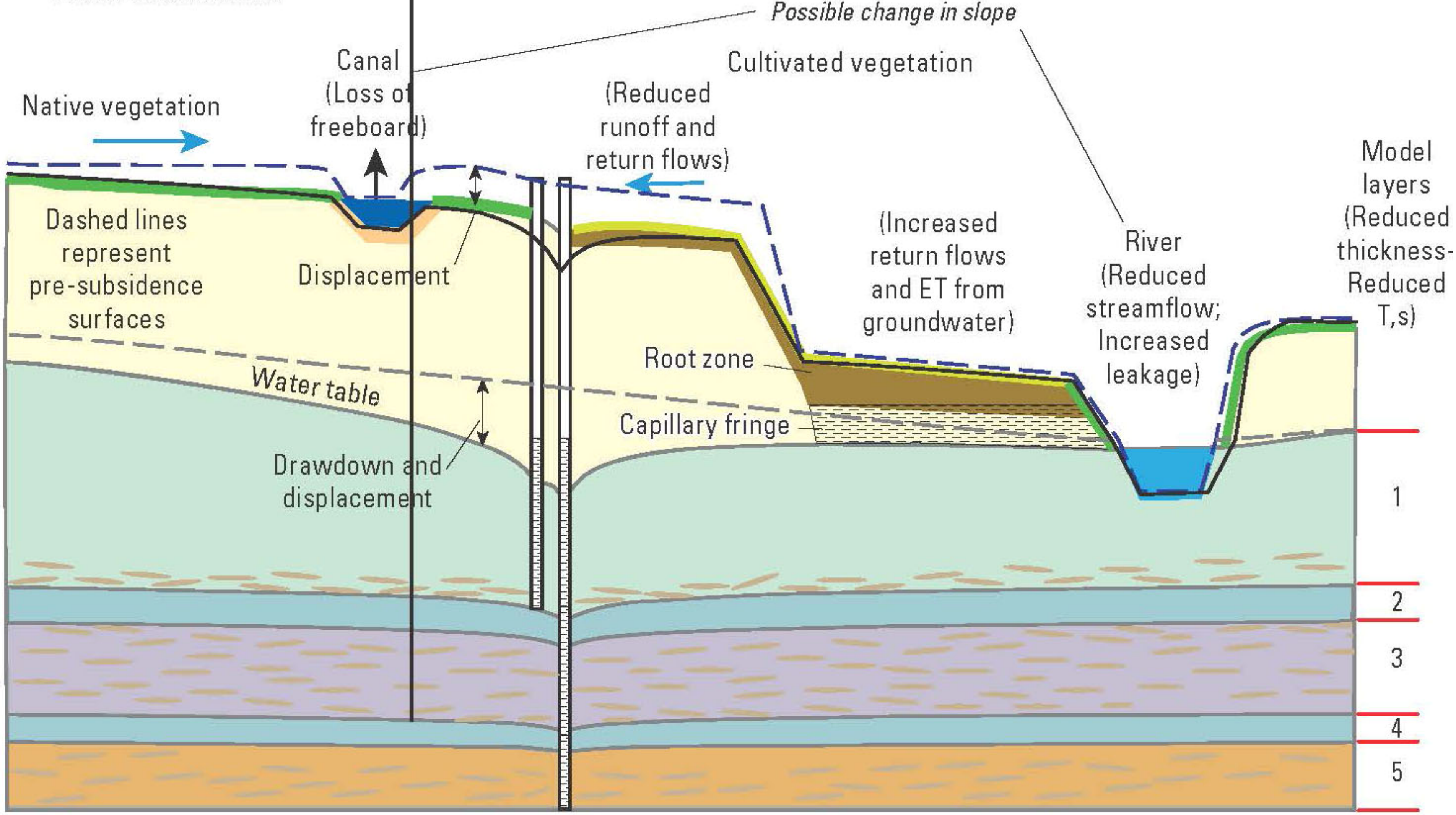
Farm Process (FMP)
Streamflow Routing Package (SFR)
Surface-Water Routing Process (SWR)

Subsurface processes

Layer-Property Flow Package (LPF)
Subsidence Package (SUB)
Multi-Node Well Package (MNW)



After subsidence



San Joaquin River Restoration Project → Detailed Child models with regional CVHM Model

Seepage in vineyard on right bank of San Joaquin River during high flows (4/13/2011)

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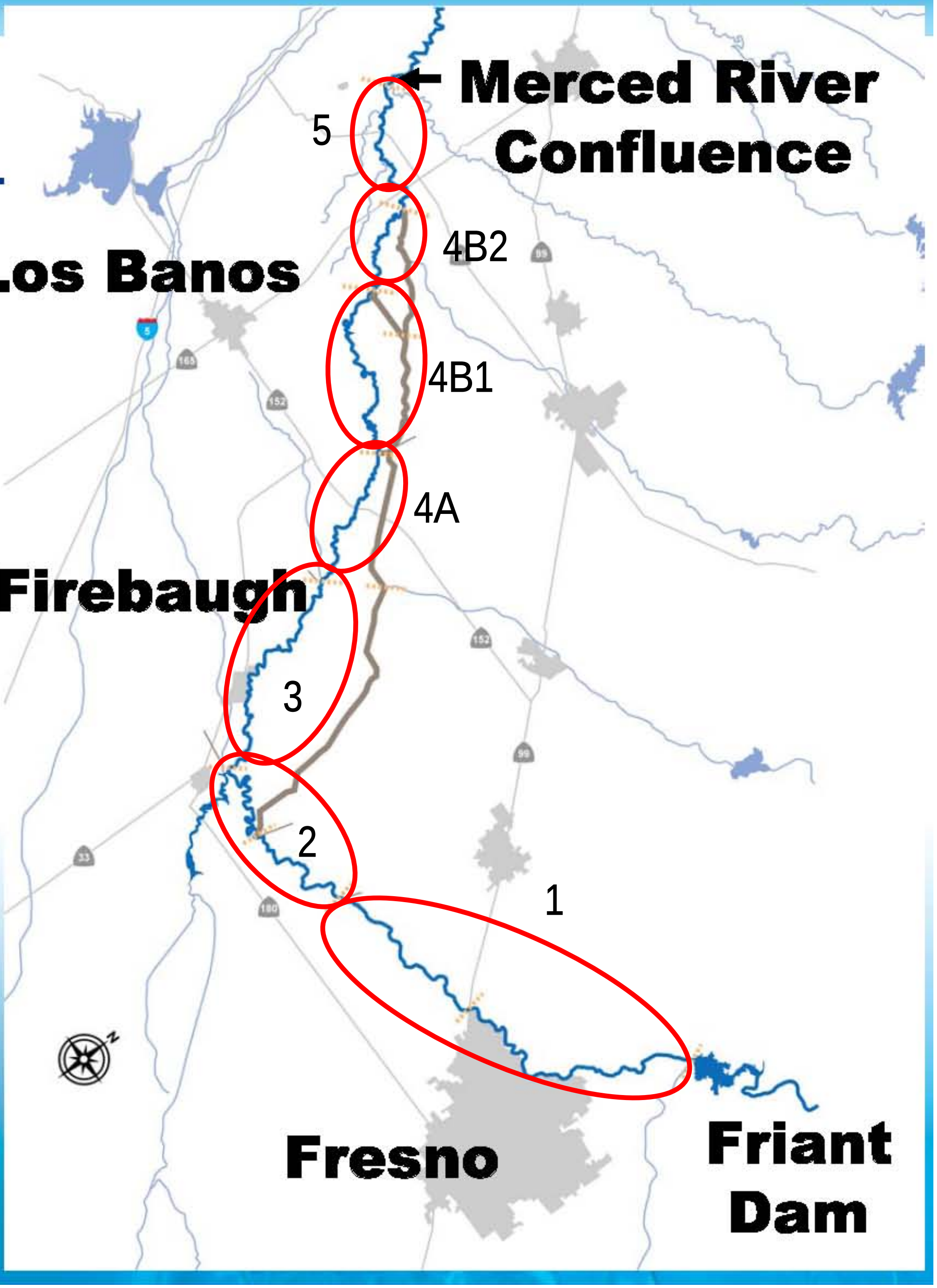
Restoration Area

- 150 River Miles
- Agriculture
- Flood Control
- Urbanization
- Mining
- 5 Distinct Reaches

CVHM Regional Model

Local Grid Refinement with FMP & SFR



Ongoing MF-FMP Developments

- **Linkage to Local Grid Refinement (LGR)**
  - **Objectives: Link FMP to LGR**
    - ➢ **Conserve Mass of Farm In- and Outflows and Balance Demand against Resources available across parent/child model domain boundaries.**
    - ➢ **link local small-scale models to a regional model without preprocessing of hydrologic data:**
  - **FIST STEP: Child model not to straddle existing farm boundaries:**
    - ➢ **inflows: supply from parent model supply sources (diversions and wells)**
    - ➢ **outflows: return flow to parent model return-flow reaches**
  - **SECOND STEP: preprocessor for numbering and setup of child model input data.**
  - **Future STEP: child models allowed to straddle current farm boundaries:**
    - ➢ **Budgets (e.g., Physical Budget, Demand and Supply Budget) available for finer-scale farms of each child model.**
    - ➢ **Sub-budgets of “residual” parent-model farm and “cut-out” child-model farm**
    - ➢ **Requirement at this stage: numbering and input data files for child models.**

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Future FMP Developments

- Linkage of FMP to Precipitation/Runoff Models
- On-farm storage (Ponds/Snow) and effluent re-use
- Add Soil Moisture Storage
- Salinity Management
- Linkage of FMP to System Dynamics (Allocation) Models

Future Features of MF-FMP

- Linkage of FMP to Precipitation/Runoff Models
    - Goal: Better Representation of Timing and Processes of Runoff.
    - Linkage to Basin-Characteristics Model (BCM).
    - Streamflow & infiltration simulated by Precipitation-Runoff models (e.g., PRMS in GSFLOW). PRMS can link with FMP models through SFR, LAKE, and UZF packages.
- On-Farm Water Storage and Release (water reuse: re-useable effluent)
- Soil moisture storage
    - Of minor importance for long-term farm budget components and/or for sufficiently irrigated farms, which do not experience long-term depletions of soil moisture.
    - Yet, multi-year depletions and changes in precipitation patterns may lead to a non-zero change in soil moisture even over one or several hydrologic years

Future Features of MF-FMP

- **Solute Transport and Salinity Management**
  - Calculation of solute concentration within and out of the root zone
  - Calculation of solute concentration of irrigation water supply and return flow
  - Update of salt build-up & salinity dependent evapotranspiration in root zone
- **MF-FMP linked to System Dynamics (Allocation) Models**
  - representation of "valley-scale" distributed hydrologic processes by MF-FMP
  - interaction between valley-scale processes and basin-scale decisions by PowerSim@, CALSIM, Riverware, etc.
- **Transition of MF-FMP to a Self-Updating Model**
  - by linkage to remotely sensed and real-time data

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Summary of Features and Advantages of FMP

- **MODEL FEATURES MADE EASY**
  - ➢ Estimates Irrigation Demand
  - ➢ Estimates Surface-Water Deliveries
  - ➢ Estimates Ground-water Pumpage
  - ➢ Estimates Net Recharge
  - ➢ Estimates all Components for ET, Runoff, and Deep Percolation
  - ➢ Integrated Hydrologic Model ➔ Complete Linkage to Groundwater and Surface-water Flow

- **ADVANTAGES FOR MODELERS**
  - ➢ No need for indirect estimates of Pumpage, Recharge, ET, Runoff, or Surface-water deliveries
  - ➢ Uses Natural Data ➔ Easy to Update Model & Less Preprocessing
  - ➢ Saves time and money for constructing, operating, and updating models
  - ➢ Facilitates Operational and Forecasting Simulations

Summary of Additional Features and Advantages of MF-FMP

- **Additional MODEL FEATURES MADE EASY**
  - Enhanced Multiplier Package exponentiation ➔ Power Mean used for VK using Texture Data arrays
  - Enhanced HYDMOD ➔ Additional Subsidence Attributes
  - Enhanced Subsidence Pkg ➔ Split Elastic/Inelastic Compaction
  - Enhanced Output with UZF components

- **Additional ADVANTAGES FOR MODELERS**
  - No need for indirect estimates of Hydraulic Properties for alluvial aquifers
  - Additional Well Types ➔ Easy to split pumpage for hydrologic Model Budgets
  - More Observation Types for Constraining Parameter Estimation
  - More Complete Hydrologic Budgets and Budget Categories

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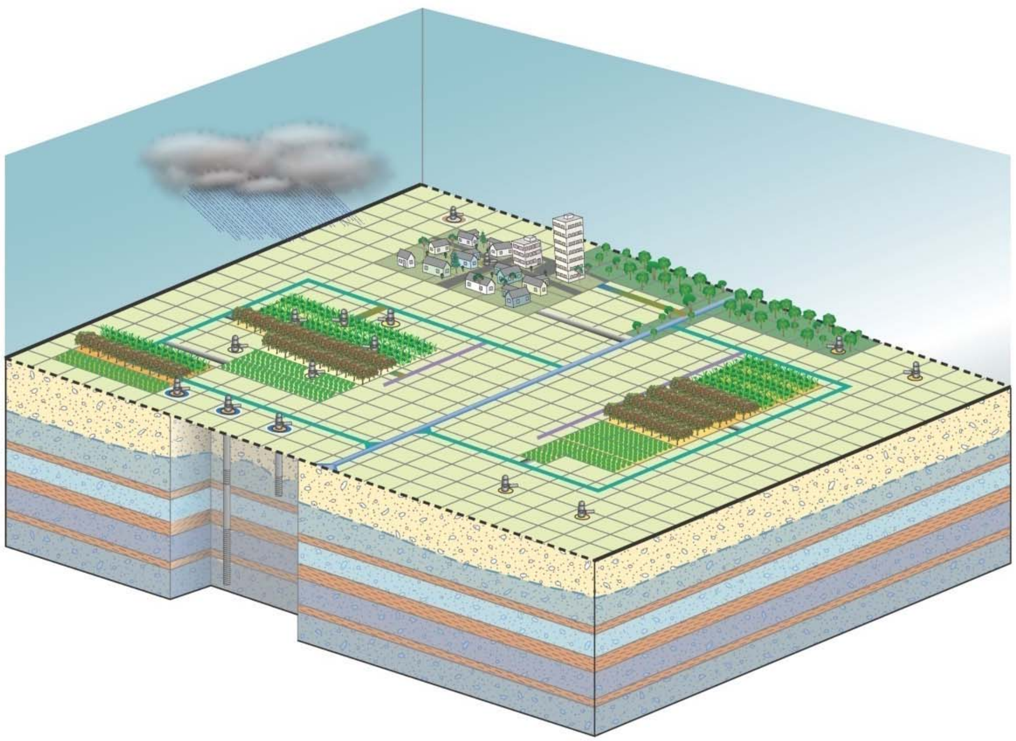
Office of Groundwater, Groundwater Resources Program

The Farm Process Version 2 (FMP2) for MODFLOW-2005—Modifications and Upgrades to FMP1



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Misnomers & Differences

- FMP has many options but is easy to use (especially in data deficient settings)
- Not all FMP options have to be used ➔ Start simple!
- FMP options can be implemented incrementally and easily changed
- FMP makes you think about hydrology plus all of the flows, climate, soils, & vegetation
- FMP requires more analysis (flows and heads)
- FMP requires more associations (wells, diversions, rivers, etc)
- FMP is easy to build
- FMP can be estimated from simple and primary data
- We are not Irrigation Schedulers➔ Demand from Soil Moisture is a separate issue managed locally by farmers

Limitations of FMP (and how to overcome some of them)

- No changes in soil moisture storage in root zone
    - by FMP for calculation of short-term irrigation requirement (but through link to UZF changes in soil moisture storage with respect to calculation of delayed recharge) → NOT for Irrigation Scheduling!!
- ET is still instantaneous source pulse out of the ground-water
    - and remains to be that way … Advantage: FMP splits ET into T and E, while UZF, RIP-ET, & other ET Packages or Processes such as PRMS, BCM, etc do not).
- One MNW1 well per model cell…. This constraint will be eliminated with connection to MNW2
- One surface-water allotment specified in "height" for entire model region.
    - e.g., acre-ft / acre = ft) for the entire domain. Farm specific allotments for surface-water deliveries are needed.

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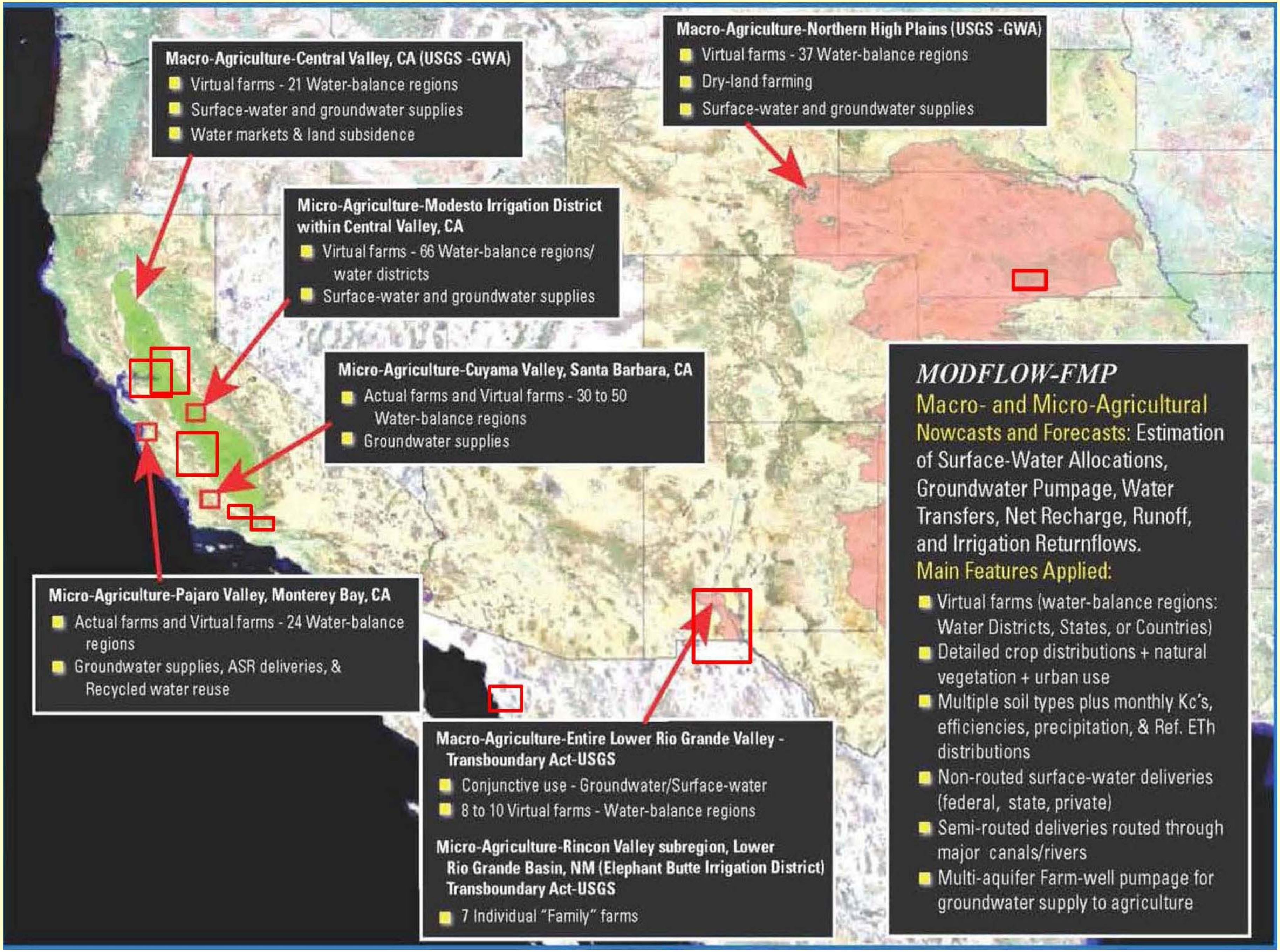
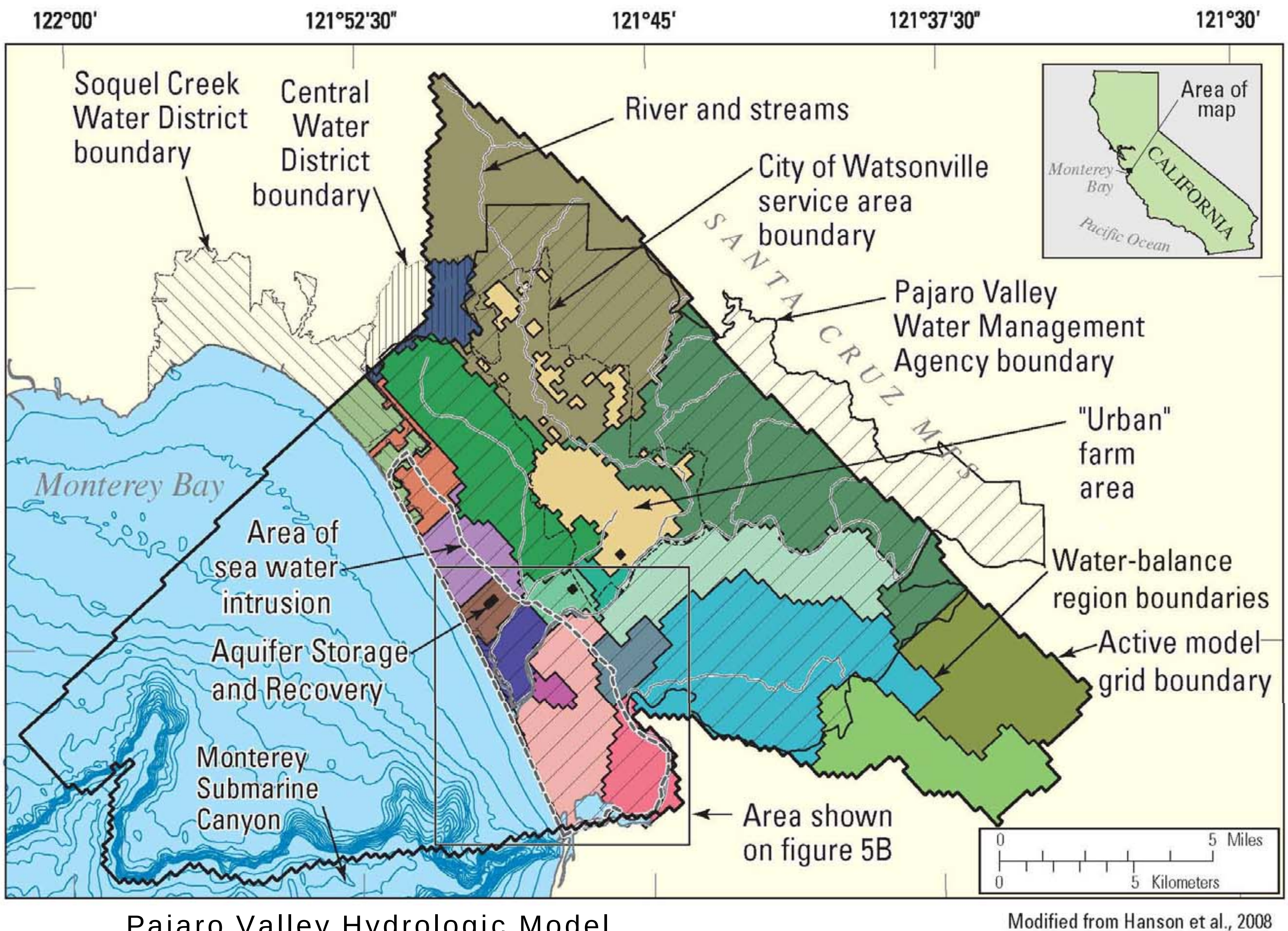
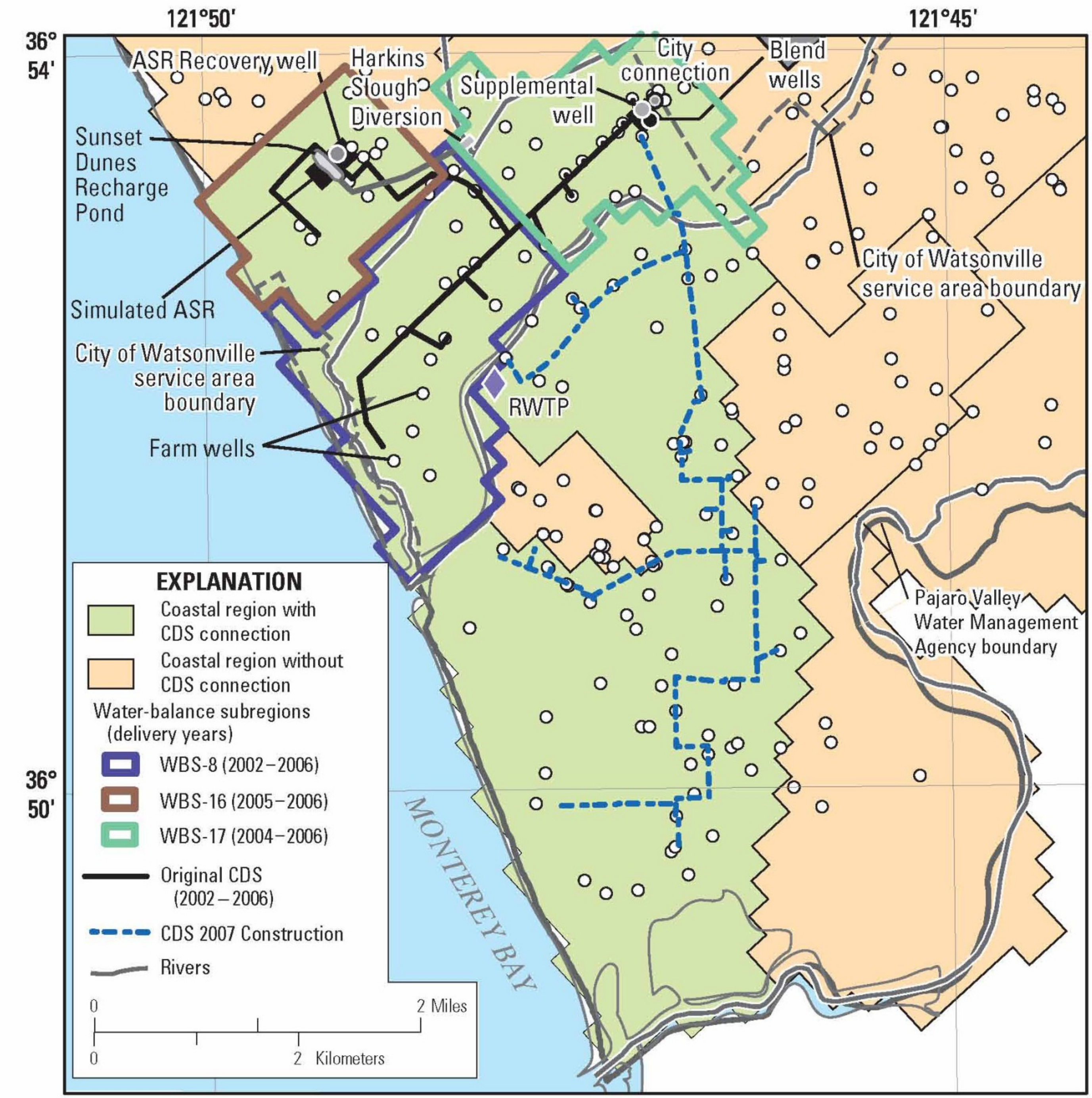
Applications in western United States/northern Mexico





Pajaro Valley Hydrologic Model

Water-balance subregions used in PVHM to assess conjunctive use, coastal pumpage, and related sea water intrusion in Pajaro Valley, California (modified from Hanson et al. 2008).



Modified from Hanson et al., 2008

Pajaro Valley Hydrologic Model

Close-up view of coastal region with the coastal distribution system, ASR, recycled water and supplemental groundwater supplies used to analyze conjunctive use and alternative supplies in Pajaro Valley, California (modified from Hanson et al. 2008).

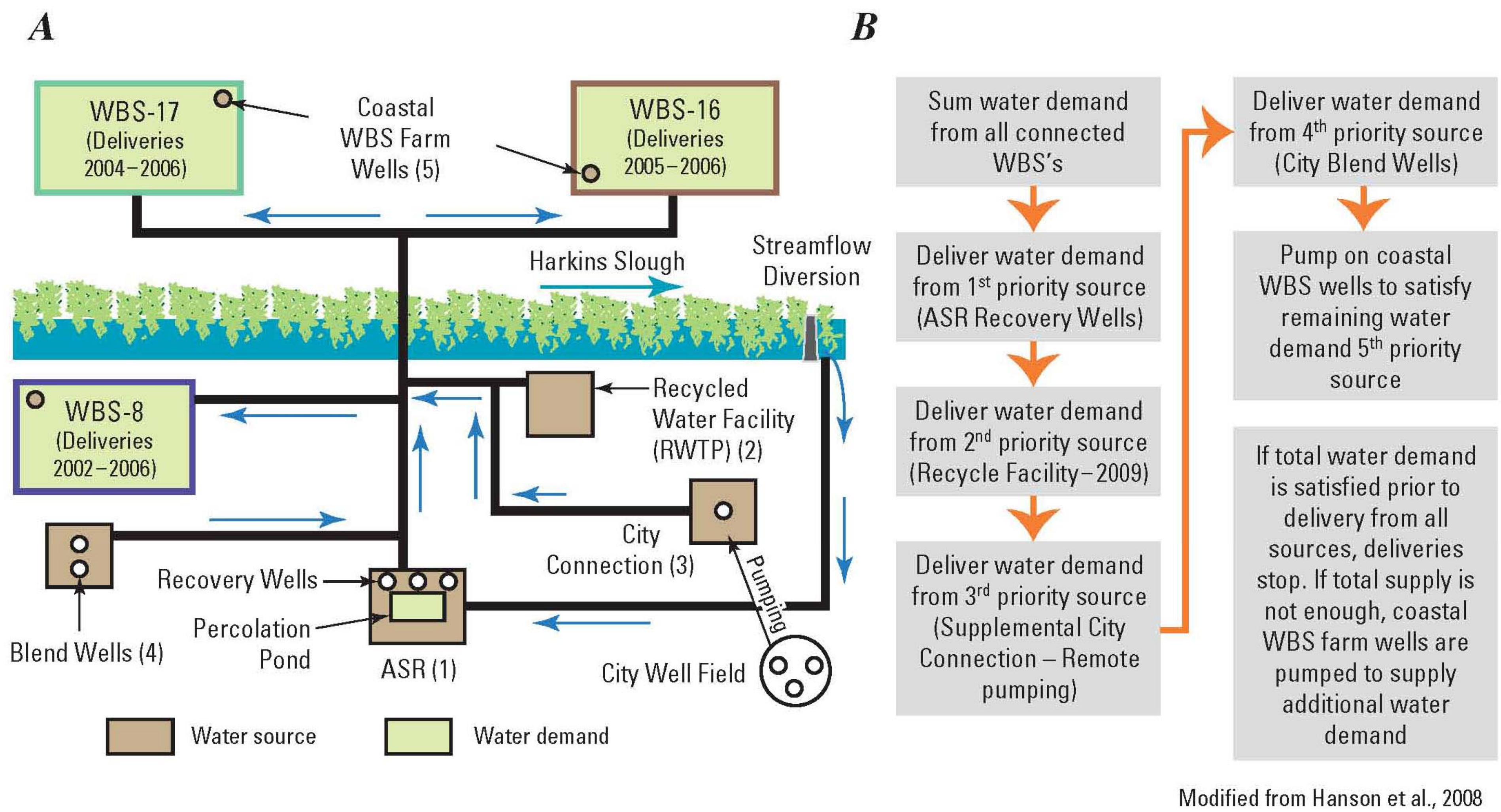
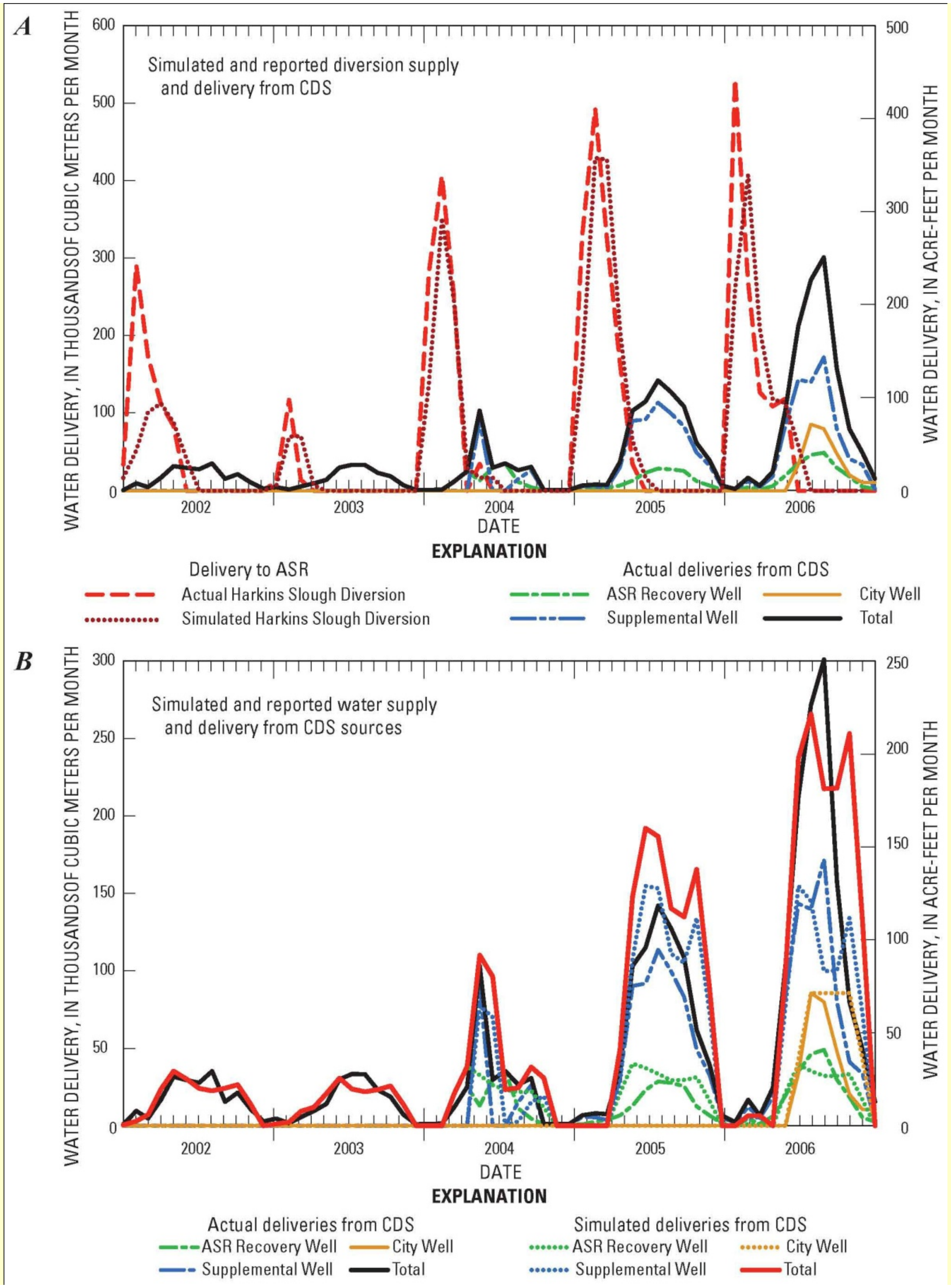


Diagram showing (A) structure of the local deliveries and (B) the hierarchy of order of operation of the ASR and CDS deliveries as part of the conjunctive use simulated by MODFLOW with the Farm Process within the Pajaro Valley, California (modified from Hanson et al. 2008).

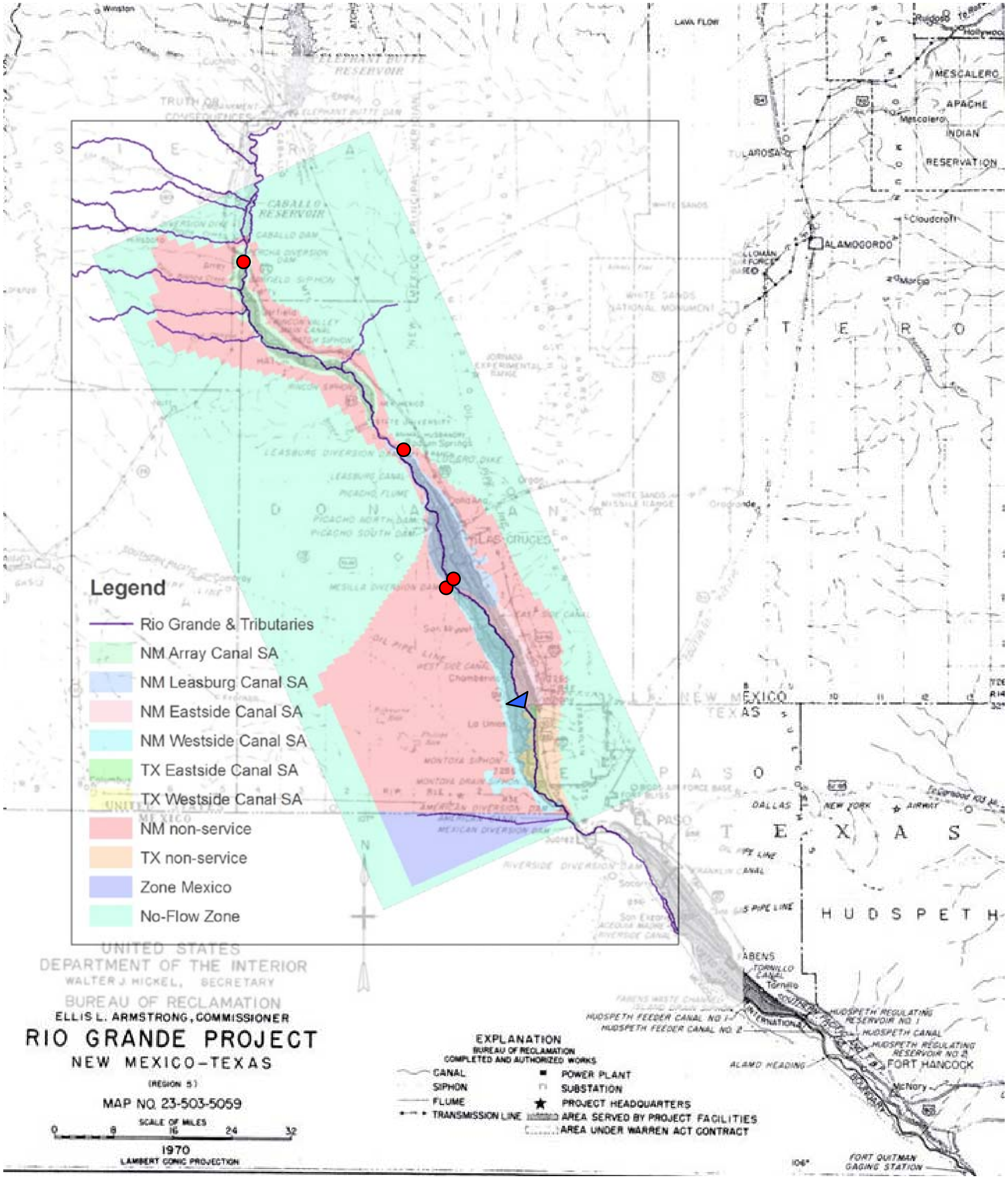


Performance of ASR and CDS System Components

Graphs showing:

(A) the temporal distribution of the surface water constrained supply and reported deliveries.

(B) The multiple farm driven demand for the combined simulation of the aquifer storage and recovery system and coastal delivery system as part of the conjunctive use simulated by MODFLOW with the Farm Process within the Pajaro Valley, California.



Analysis of River Compacts from GW/SW Deliveries & Pumpage

LRGHM model covers only EBID but not EP1

BUT

LRGHM simulates surface-water allotments as call on the Reservoir & can compare

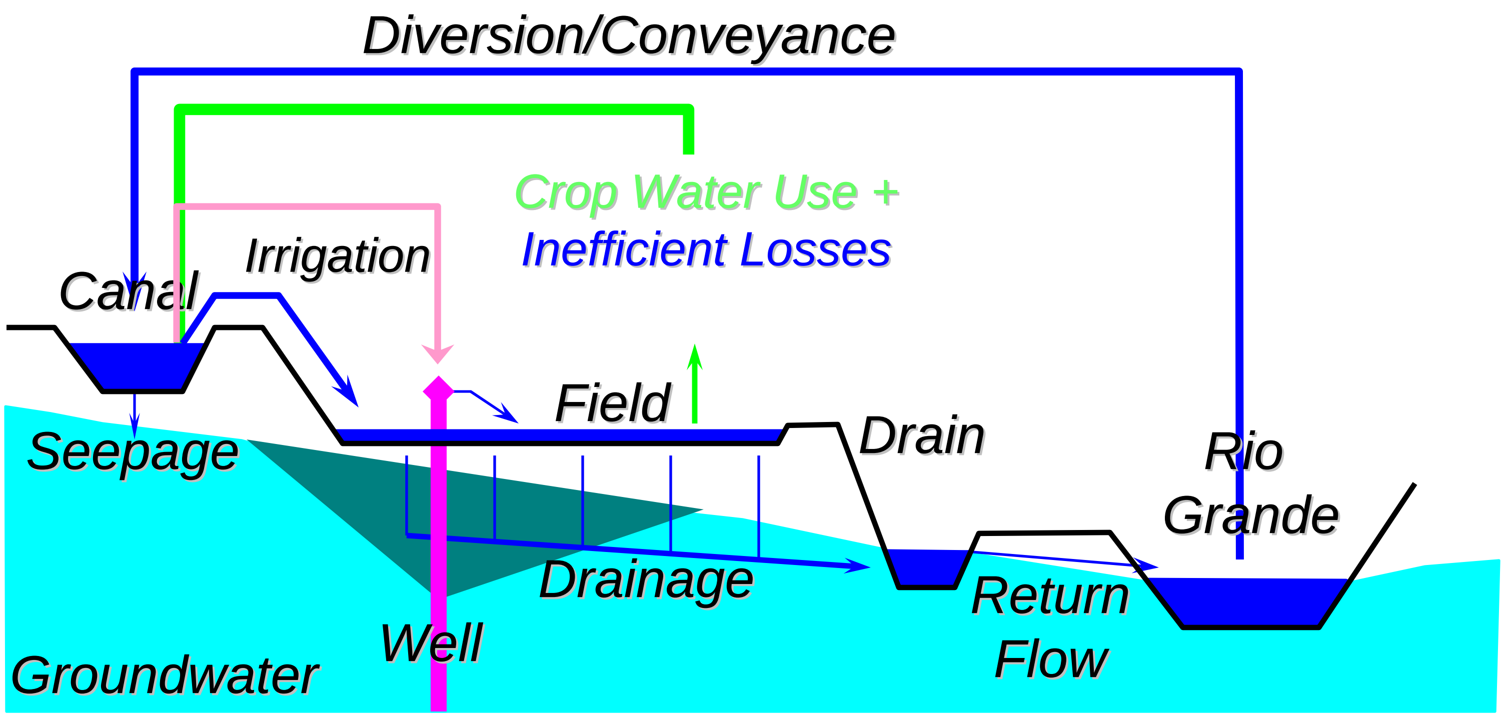
Diversions:

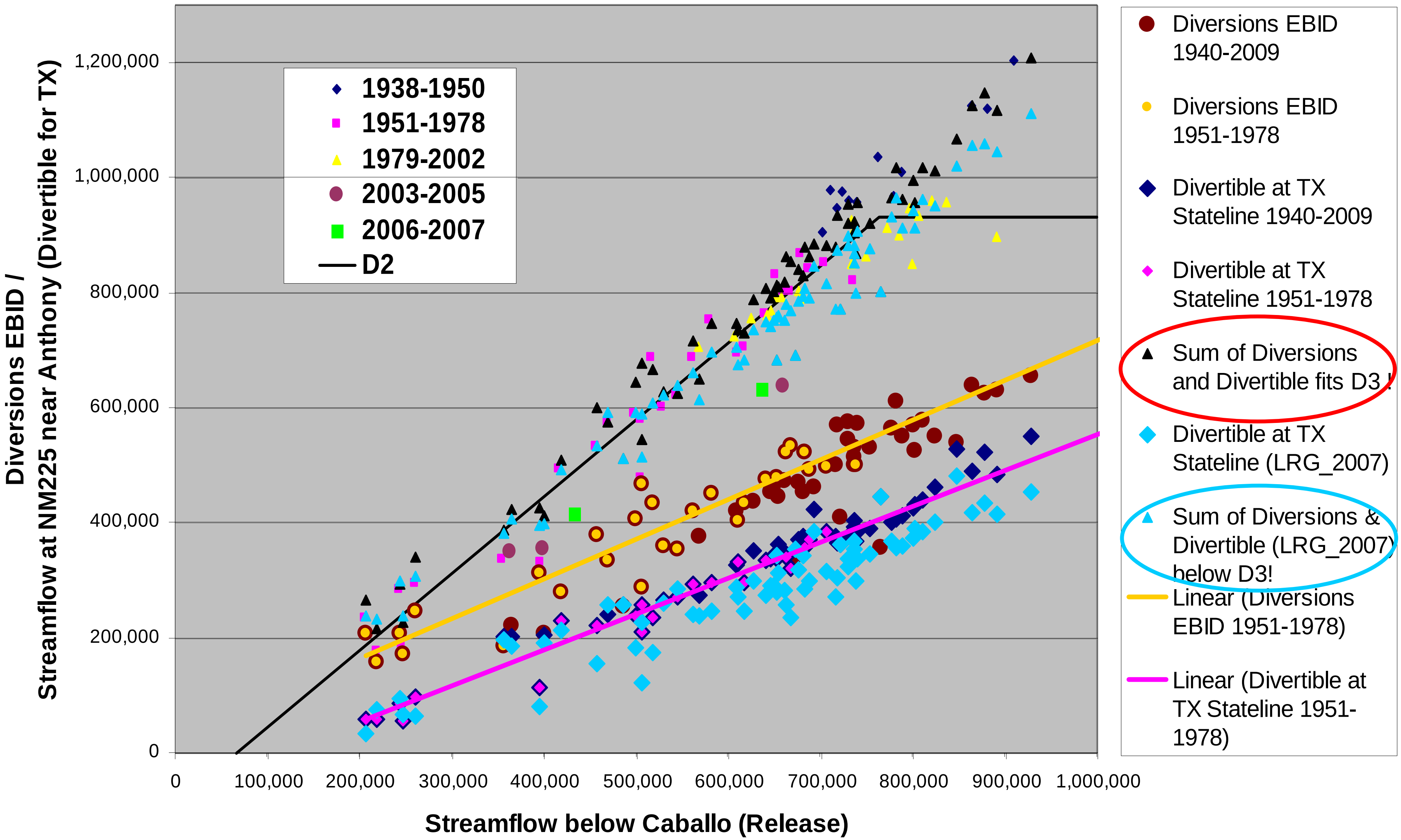
- Diversions to EBID
- “Divertible” Water at TX Stateline for TX and MX ➔ D2 & D3 Curves of Release vs Deliveries

Actual Deliveries to Farms:

- Deliveries to EBID Farms
- NOT YET: Deliveries to EP1

Problem: Release to diversion hydrology altered by groundwater pumping in New Mexico




1938-1950
1951-1978
1979-2002
2003-2005
2006-2007
D2
Diversions EBID 1940-2009
Diversions EBID 1951-1978
Divertible at TX Stateline 1940-2009
Divertible at TX Stateline 1951-1978
Sum of Diversions and Divertible fits D3 !
Divertible at TX Stateline (LRG_2007)
Sum of Diversions & Divertible (LRG_2007) below D3!
Linear (Diversions EBID 1951-1978)
Linear (Divertible at TX Stateline 1951-1978)
Diversions EBID / Streamflow at NM225 near Anthony (Divertible for TX)
Streamflow below Caballo (Release)
0
200,000
400,000
600,000
800,000
1,000,000
1,200,000
0
100,000
200,000
300,000
400,000
500,000
600,000
700,000
800,000
900,000
1,000,000

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Conclusion ➔ Why Use MF-FMP?

(1) Integrated Hydrologic Model ➔ Physically Based simulation of Surface Water, Groundwater, & Landscape water

(2) Conjunctive Use Supply-and-Demand Modeling Framework ➔ Connected to Natural and Human Uses & Movement of Water

(3) FMP's Mission ➔ Simulates All the Water – All the Time – Everywhere in the Simulated Hydrosphere

(4) Directly Addresses the Supply & Demand Components and interchanges of Conjunctive Use ➔ Supply Constrained & Demand Driven Use and Movement (Flows) of Water throughout the Hydrosphere