3. OVERVIEW OF MODELS

The purpose of this section is to explain the approach by which COHYST 2010 (Sponsors and technical team) designed the modeling effort, and to introduce the selected modeling tools. Typically, surface operations or groundwater models evaluate management actions on only one portion of the water budget, which can lead to 'double-counting' water, particularly in highly interconnected hydrologic settings. To ensure that the same volume of water is not allocated independently to both the surface and groundwater uses, COHYST uses an integrated model approach which tracks all aspects of the water budget, as water moves over the landscape, into the aquifer, and into streams. The integrated model also tracks water as it moves from streams to the aquifer and conversely, from the aquifer to streams.

3.1 Conceptual Model

<u>Results desired</u>. COHYST 2010 differs from prior Platte Basin models in two primary ways. First, a goal of COHYST 2010 is to encompass the <u>entire water balance</u>, which requires an integrated model of water on the land, in rivers, and in aquifers. The previous COHYST groundwater modeling efforts lacked constraints for some variables, such as recharge, and calibration of these variables often resulted in unrealistic values. To resolve this, COHYST 2010 is relying on an integrated modeling approach to constrain these variables, an approach that is necessary due to the highly interconnected hydrologic system that is heavily modified by human activities to support large quantities of surface and groundwater users. Second, the primary use of the model is to evaluate changes in water management, which emphasizes the importance of adequately characterizing the spatial-temporal changes in <u>agricultural water uses</u> and practices to understand these impacts to the hydrologically connected streams and aquifer.

<u>Hydrologic cycle</u>. The complete hydrologic cycle as modified by irrigation and other human activity is the conceptual model of the Platte River. **Figure 3.1-1** is a schematic illustration of the hydrologic cycle for a system where use of water for irrigation is important. This figure provides visual context for subsequent discussion of how the system is modeled.

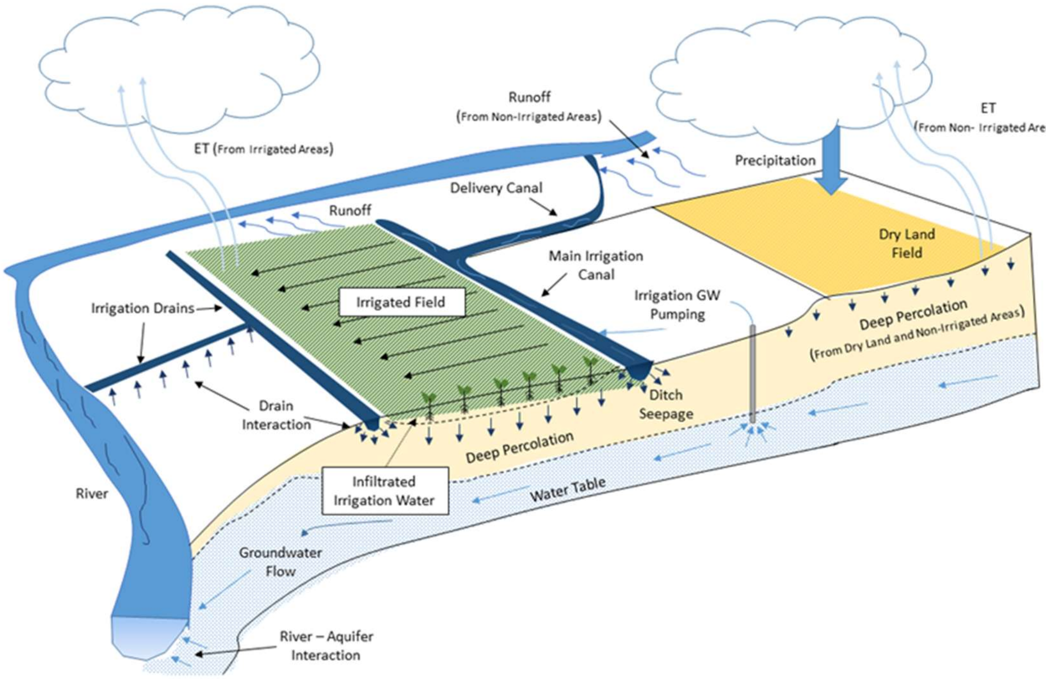

Figure 3.1-1. Illustration of Hydrologic Cycle in which Irrigation is Important.

Components of the cycle. An initial step in building the actual models was to specify those elements of the hydrologic cycle that are to be considered; these are listed in **Table 3.1-1**. The overall water balance of the system is that outflows must equal inflows, plus or minus changes in storage.

Table 3.1-1. Components of the Platte River Hydrologic Cycle.

Inflows (sources of water)
• Surface inflows at Julesburg on the South Platte and Lewellen on the North Platte Rivers. • Groundwater inflows to the entire area from the west. No other major subsurface inflows occur in the study area. • Precipitation on the landscape within the entire study area.
Outflows (sinks of water)
• Surface outflows on the mainstem Platte at Duncan. • Groundwater outflows to the east. • Groundwater discharge to the Loup, Blue and Republican River basins. • Evapotranspiration from the landscape including areas of open water.
Storage of water
• Surface water reservoirs with a large capacity and variable storage: Lake McConaughy, Sutherland Reservoir, Elwood Reservoir. • The regional aquifer. • Water in unsaturated or intermittently saturated zones: soil, vadose zone, reservoir, and river

banks. [See text below for discussion of this element.]
Internal Exchanges (relate to the natural and managed hydrology within the system)
• Water that is diverted from streams or pumped from the aquifer and put on the land to meet crop needs not satisfied from rainfall is known as applied water. • Precipitation and applied water are consumed (evapotranspiration), or become runoff or recharge. • Water is added to or released from reservoirs into rivers or canals in accordance with factors such as irrigation or power demands. • Surface waters may gain water from or lose water to the aquifer; groundwater may gain water from or lose water to streams and irrigation drains.

After discussion, the Sponsors and technical team agreed to remove unsaturated or vadose zone water storage as a variable to be modeled directly, and instead model its effects on recharge amounts indirectly by adjusting recharge rates in certain areas of the model with a large unsaturated zone. The decision to not model the vadose zone directly was influenced by the complexity and time intensiveness of such modeling, and that this level of complexity would not contribute significantly to understanding the effects of different water management strategies. See Section 7 for further discussion.

3.2 Model Dimensions

The spatial-temporal dimensions for each of the 3 models considered the physical geography of the area of investigation, and the timing of the landscape, surface water, and groundwater systems to compute a complete water balance within the model domain. The integrated model focuses on the effects of surface and groundwater irrigation within the Central Platte Basin; therefore, the model boundaries must include the major surface water irrigation systems, as well as extend beyond those systems to prevent groundwater model boundary effects.

Model area. The spatial coverage for the landscape, surface water, and groundwater models differ. The groundwater model domain needed to extend beyond the surface water basins of interest to prevent boundary condition effects, while still capturing all components of the groundwater water budget for each sub-basin, as shown in Figure 1.1-1. The current model domain continues from the boundaries established in prior COHYST work (see Groundwater Flow Model Reports for the Eastern and Central Model Units 2007 & 2008). Groundwater model boundaries include drainage divides between basins, rivers in adjoining basins, and at defined upstream and downstream aquifer limits. The landscape-CROPSIM model has the same spatial domain as the groundwater model.

The surface water operations model considers only locations where Platte River water is stored, diverted, used, or returned for irrigation or other purposes. These include the river itself, and associated reservoirs, canals, drains and lands, all of which are inside the Platte River drainage basin shown in Figure 1.1-1.

Spatial resolution. The COHYST 2010 model continues at the same spatial resolution as prior modeling efforts that used ¼ square mile, 160 acres, grid cells. The 160 acre grid cells provide a scale that is similar to the typical size of an irrigated parcel of land. The grid is aligned with the cardinal directions in NAD 1983 Nebraska State Plane FIPS (Feet) coordinates and consists of square cells 2640 ft by 2640 ft. The southwest corner of the grid is at 1,044,120 ft E and 68,640 ft N. The entire grid contains 504 columns and 275 rows, with a total of 138,600 cells, of which 77,339 are active.

The surface water spatial resolution includes all points required to measure the effects of water operations. These are points include Platte River measuring gages, storage/reservoir locations, points of diversion, and points of return.

Model time frame. The 2013 COHYST groundwater model focuses on the regulatory program 1997 accounting point, which resulted in a different time frame than the latest version of the groundwater model. The newer model version includes 1985-2005 as an extended calibration period to capture conditions before and after 1997. The 1985-2005 timeframe also represents a period of which comparatively abundant data are present. These datasets include detailed hydrology, geohydrology, land-use, water management, and climate.

The model documented in this report includes an extension to 2010; results for the 2006-2010 were used to verify the suitability of the model for management purposes. The COHYST 2010 models have also been extended back in time to 1947 to simulate Platte River Program water management alternatives. The 1947 thru 1995 period was original used for Platte River operations analysis that setup major water operation changes in the Platte River to benefit T&E species.

Temporal resolution. The model timescale needs to have intervals short enough to be useful at the scale of management decisions, but not so fine as to make model operation difficult or model results noisy. A monthly time-scale was judged appropriate for obtaining results that differentiate between the irrigation and non-irrigation seasons and that show inter-annual variations (e.g. dry versus wet years). For the time frame selected (which begins October 1984 to provide a start that reflects a complete water year), this equates to 315 months for which outputs are generated. The surface water component utilizes a daily timeframe which is cumulated to monthly for interaction with the groundwater model.

3.3 Observed Water Balance

Combining 3 different water models leaves considerable concern for maintaining mass balance within each model and during the integration process. To check for mass balance errors, a complete water balance was computed over the 1985-2005 timeframe, for the entire model area. The final methods and results of the computed water balance, based on historical data, are in **Appendix 3-A**. Results from the water budget calculations are summarized in **Table 3.3-1** and illustrated in **Figure 3.3-1**. This result is referred to as the Phase I water balance, though the balance has been updated since Phase I was completed. During model calibration, the water balance has been compared to model results and revised when that comparison indicated possible methodology errors regarding interpretation the historical data. The use of the balance in calibration is reported in Section 8.

Table 3.3-1. Observation Based Water Balance to Represent the Entire Hydrologic Cycle in the COHYST 2010 Study Area for the Entire Period 1985-2005. AF = average acre-feet/year.

		Units (ac-ft/yr)	**Percentage**
Inflow			
1A	Precipitation on the land surface	23,177,411	94.3%
1B	Precipitation on the water surface 1)	0	0.0%
1C	Surface water inflows from upstream 2)	1,327,879	5.4%
1D	Subflow from upgradient (all boundaries)	65,619	0.3%
Total Inflow	1A + 1B + 1C +1D	24,570,909	100.0%

Outflow			
2A	Evapotranspiration from the land surface	-22,889,486	92.5%
2B	Evapotranspiration from the water surface 3)	0	0.0%
2C	Surface water discharges downstream 4)	-1,785,549	7.2%
2D	Subflow to downgradient (all boundaries)	-77,712	0.3%
Total Outflow	2A + 2B +2C +2D	-24,752,747	100.0%

Changes in Storage		
3A	Net change in soil moisture 5)	0
3B	Net change in bank storage 5)	0
3C	Net change in reservoir storage within study area	-49,881
3D	Net change in aquifer storage	-131,956
Net Storage	3A + 3B + 3C + 3D	-181,837

Notes:
1) 1A and 1B represent 100 percent of the precipitation within the model domain
2) Includes native flow, storage water releases, and imported water
3) 2a and 2B represent 100 percent of the evapotranspiration within the model domain
4) Includes Platte, Republican, Blue and Loup rivers.
5) These changes in storage are ignored for the 1985 to 2005 calculation

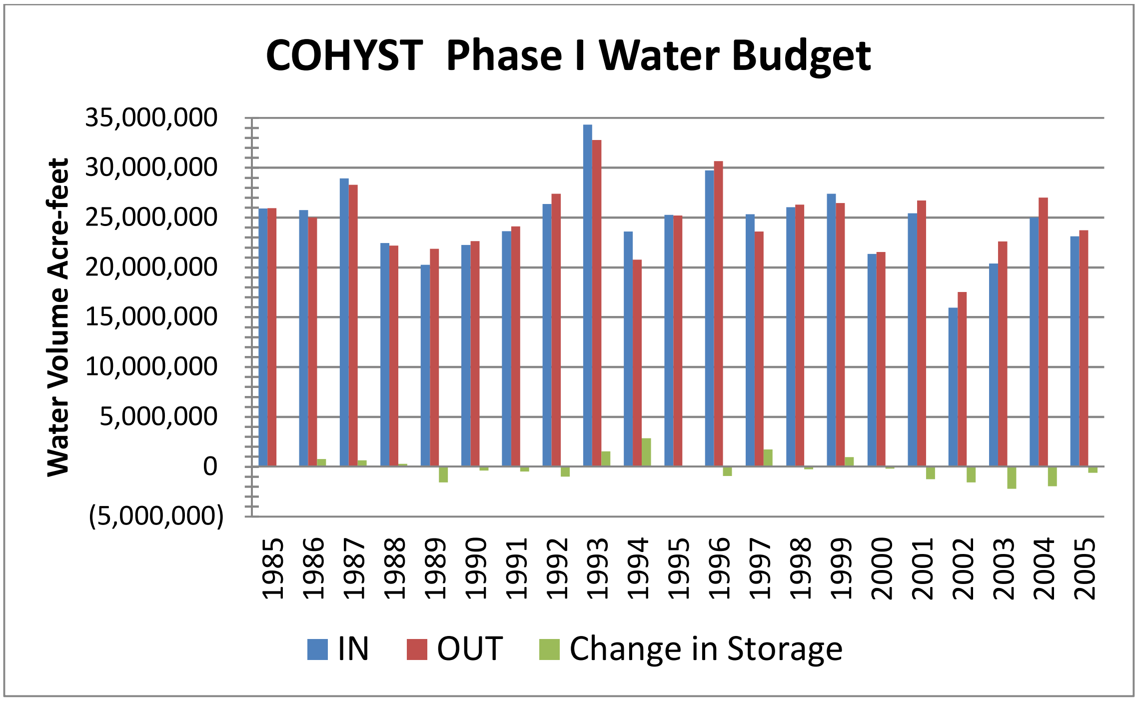

Figure 3.3-1. Annual Values of Phase I Water Balance for Inflow, Outflow and Change in Storage.

3.4 Technical Approach

The model structure adopted by COHYST 2010 is shown in **Figure 3.4-1**, which places the elements of Table 3.1-1 into a graphical form that is consistent with the hydrologic cycle of Figure 3.1-1. The figure breaks the hydrologic cycle into three parts: land, river, aquifer. Modeling tools were chosen to simulate each part of the system –watershed model for land, surface water model for river, and groundwater model for aquifer. In addition, there are exchanges of model results among the models. The model structure is shown **in Figure 3.4-2**.

Land/soil water. The objective of a land/soil water model is to calculate water demands for irrigation, and the fate of rainfall and applied water on the land. This requires use of a method to simulate the soil water balance as a function of climate, soil, and land use. At the time the Conjunctive Management study was in development, consultants were asked to propose a method for modeling of land/soil water. The selected approach was a **watershed model** developed by The Flatwater Group. The model relies on CROPSIM, a farm water balance model widely used in Nebraska. Its application for COHYST 2010 required no structural changes. Model documentation is provided in Section 5 of this report.

Surface water. The objective of a surface water model is to simulate the storage, release, diversion, use and return of water along the Platte River and in canals that draw from the river. This requires a method which can replicate operation of the system (reservoirs and canals) and routing of water to meet surface water demands. The approach selected by Conjunctive Management was a **surface water model** developed by HDR, Inc. using the STELLA system dynamics modeling platform with a graphical structure. This model was created from scratch based on known surface water infrastructure and operating protocols. Model documentation is provided in Section 6 of this report.

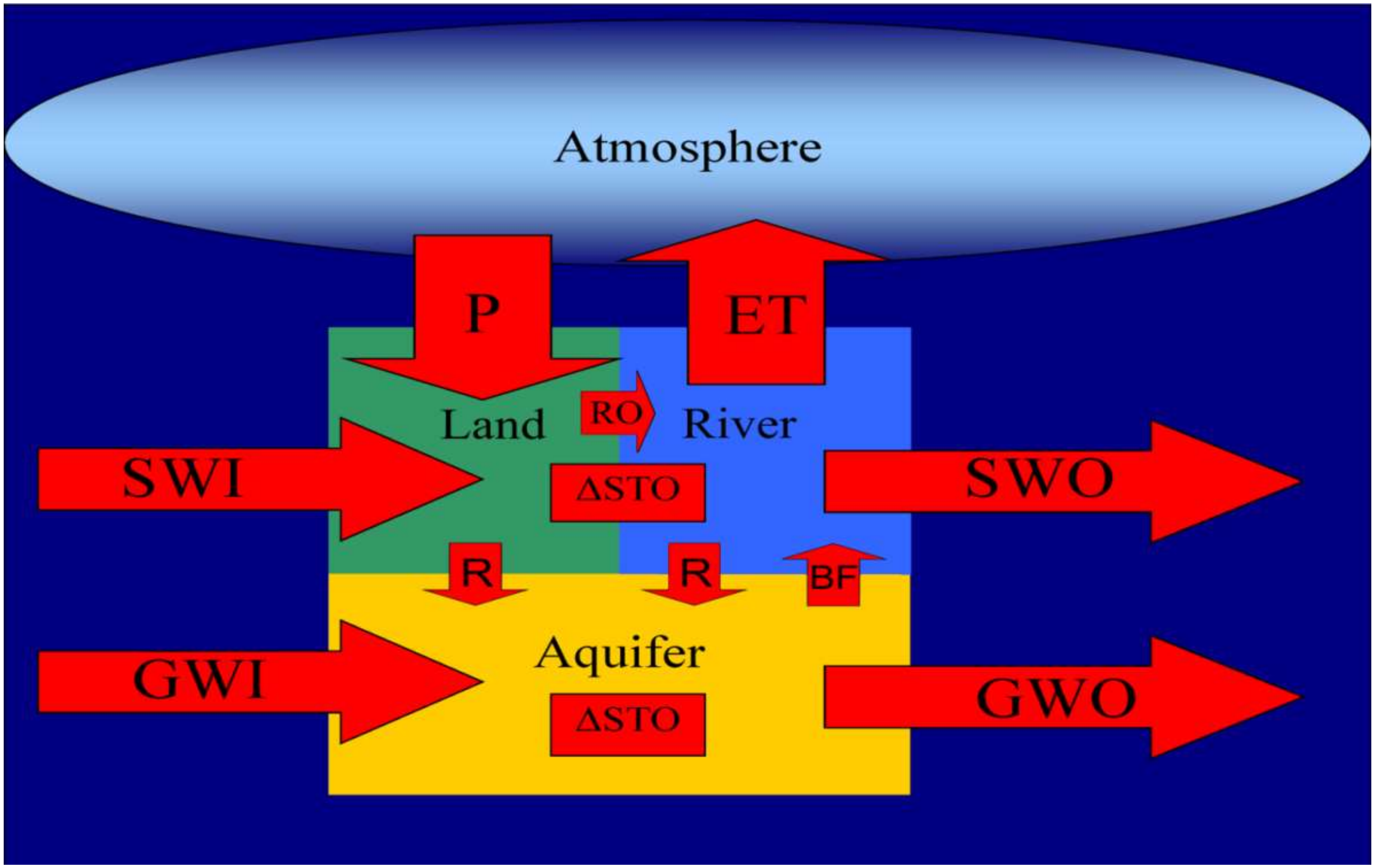

Figure 3.4-1. Relationships of Components of the Hydrologic Cycle (as listed in Table 3.1-1.).

CODES are as follows:

Green = land/soil water balance.
Blue = surface water balance.
Yellow = aquifer water balance.
P = precipitation.
R = recharge
RO = runoff

BF = baseflow discharge
ET = evapotranspiration (can include open water evaporation).
SWI and SWO = surface water inflow and outflow.
GWI and GWO = groundwater inflow and outflow.
ΔSTO = change in storage.

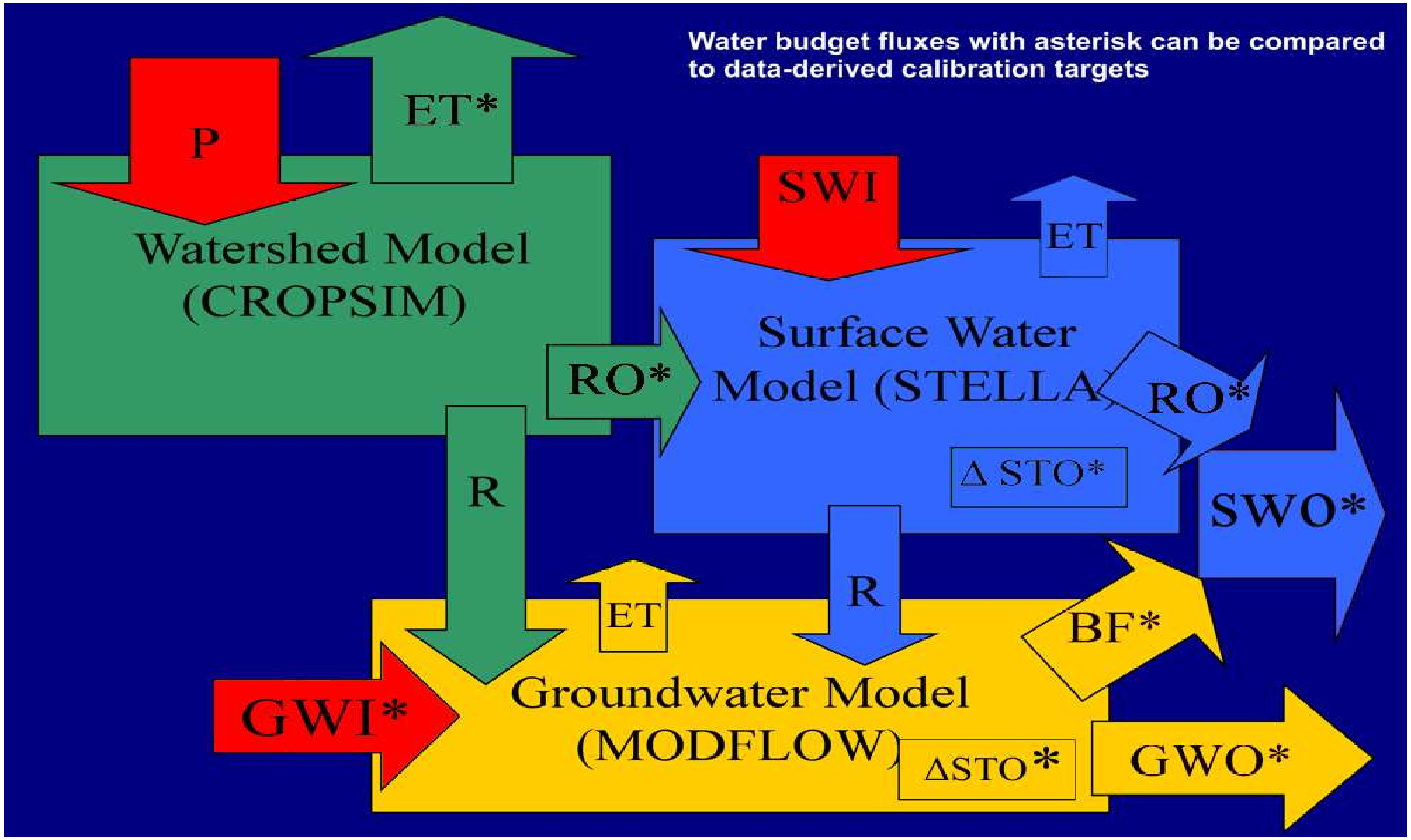

Figure 3.4-2. Structure of the COHYST 2012 Models to Reflect the Hydrologic Cycle of Figure 3.4-1.

Green = watershed model domain and outputs.
Blue = surface water model domain and outputs.
Yellow = groundwater model domain and outputs.
Red arrows are external model inputs.

Groundwater. There are two main objectives of the groundwater model, 1) quantify changes in aquifer water levels (thus water in storage) resulting from recharge to and pumping of the aquifer, and 2) simulate the effects of groundwater pumping on streams. The primary requirements to meet the groundwater model objects are: knowledge of aquifer properties, hydrologic connectivity between the streams and aquifer, land-use changes, and the volume of surface and groundwater diversions. The prior groundwater models were built using the USGS MODFLOW code and were considered suitable as the starting point for COHYST 2010. The Sponsors decided that the prior models be simplified from six layers to one to ease operations and address model instability issues. The Nebraska Department of Natural Resources completed the 2013 groundwater model, while Lee Wilson and Associates (LWA) updated and completed the 2017 groundwater model. Model documentation for the 2017 groundwater model is provided in Section 7 of this report.

3.5 Model Integration

An important component of COHYST 2010 is that information generated in one model can be used as input to or as a calibration target for another model. The primary information exchanges are listed below.

- Water diversions in the surface water model and well pumping in the groundwater model are computed by the watershed model.
- Recharge to the groundwater model is computed by the watershed model for deep percolation from the land, and computed by the surface water model for canal seepage. The stream routing in the groundwater model requires inputs from the surface water model.
- The surface water model gains runoff as calculated by the watershed model, and baseflow as calculated by the groundwater model. It can lose water to channel seepage if the river stage is higher than the water table.

Integrated model. The surface water model developed relied upon historical gage records, reservoir levels, and diversion records to develop the rules necessary for the model to simulate actual routing in the central Platte Basin. Historical records and anecdotal knowledge also provided the basis for the surface water model calibration. The use of historic data was instrumental for development of the surface water model, but is not used during analysis of water management alternatives using the integrated model. The integrated model relies upon inputs from the watershed model (surface water runoff) and groundwater model (aquifer discharge to streams) to calculate the available water at each accounting point, as well as then determine where the water routes based on the rules within the model. Switching from the historical to the integrated mode represents the final step in the modeling and calibration process, meaning that the model is sufficiently calibrated for scenario analysis. **Table 3.5-1** summarizes the differences between the integrated and historic modes of model operation. The integrated model is discussed further in Section 8.

Historically, running of the integrated model required manual exchanges of information between models, i.e. results of one model were posted for downloading by users of other models. As of this report, it is possible to run the model using a Graphical Unit Interface; see Section 8.

3.6 Modeling Process

The modeling work described in this report began in early 2011. Calibration of the model for 1985-2005 conditions was completed and documented in 2013. Extension of the model through 2010, and recalibration, was completed in 2017 and is documented in this report. The development of the model involved extensive coordination among members of the modeling team and continuing review by technical representatives of the Sponsors. The level of coordination and need for consistent calibration procedures led the Sponsors to develop the Calibration Plan.

Table 3.5-1. Difference Between Historic and Integrated Models.

Historic

In historic runs, there is no feedback regarding runoff and baseflow. Instead, the surface water model uses an input called "reach gain-loss" or RGL, which is calculated from observed data. For any reach between two gages, RGL is the difference in flow between the downstream and upstream gages, adjusted for gaged diversions and returns. An example is given below.

On a given day, downstream gage shows:	1,200 cfs
On that day, upstream gage shows:	1,000 cfs
On that day, gaged canal diversions are:	100 cfs
On that day, there are no gaged returns	0 cfs

In this example, and assuming that the gaged values are perfectly accurate, the value of RGL is 300 cfs – the amount of water that must have reached the river, such as through ungagged tributaries or baseflow contributions, between the two gages, to account for the observed 200 cfs gain in flow and to make up for the observed 100 cfs of diversions. RGL input values have been calculated daily for each gaged reach in the surface water model. Because RGL is a computed value for historic runs, large and systematic errors in such runs typically indicate a need to revise the model operating rules.

Integrated

While RGL can be calculated for purposes of calibrating surface operation rules, it must be simulated for overall calibration and for any application of the models for management alternatives. Based on the hydrologic cycle, the components that make up RGL are as follows:

runoff from the watershed model;
baseflow from the groundwater model;
ungaged surface return flows (which can be estimated inside the surface water model);
direct evaporation from surface waters (can be calculated from surface areas and evaporation rates and unlike items above, is a deduction from RGL).

The RGL value that results from use of modeled values is often not the same as that computed from the observed data, as shown in the example below.

On a given day, downstream gage shows:	1,200 cfs
On that day, upstream gage shows:	1,000 cfs
On that day, gaged canal diversions are:	100 cfs
On that day, there are no gaged returns	0 cfs
On that day, watershed model estimates runoff:	10 cfs
On that day, groundwater model estimates baseflow:	50 cfs
On that day, surface water model estimates ungaged returns	10 cfs
On that day, surface water model estimates direct evaporation	-10 cfs

In this example, the calculated reach gain loss is 60 cfs (the sum of the last four values above), far less than the 300 cfs that was estimated based on the gaged data. For this example, the professional judgment of the modeling team would be that the most likely explanation for the difference is that the runoff estimate from the watershed model and/or the baseflow estimate from the groundwater model are too low. This would indicate a need to consider changes to the watershed model and/or groundwater model to improve calibration.

The Calibration Plan, written in 2010 and updated in 2013, outlines the model calibration process and targets for the individual and integrated models. The significant modifications for the 2016 model necessitated a new document, the Re-Calibration Plan to outline the updated and new approach to calibrate the integrated models. The updated 2013 Calibration Plan and May 2016 Recalibration Plan are provided here in **Appendix 3-B**; some content of the 2013 updated plan is out of date, but the basic principles still apply. The calibration approach requires that the individual models are constructed and calibrated separately, prior to integration and calibration of the entire water budget. The plan specifies that calibration success will be determined through professional judgment, augmented by statistical measures. Primary calibration targets are stream flows and aquifer water levels; secondary targets include reservoir levels, canal diversions, and baseflow estimates. Recharge, irrigation demand, surface water operation rules, and aquifer parameters are the primary model adjustments to achieve calibration.

Professional judgment is guided by the knowledge that the total water balance for the study area exceeds 24,000,000 acre feet per year (see Table 3.3-1). Thus, absolute errors in water balance terms measured in tens or even hundreds of thousands of acre-feet per year are small compared to the whole, and may be acceptable. The integrated model will be used to compare different management scenarios, as such, many absolute errors will cancel. For calibration, the focus has been on understanding and reducing discrepancies between the model results and observed data, which are errors that are systematic and accumulate over time. These errors include: inconsistencies with observation vs simulation trends, errors with a strong regional bias, different performance in wet versus dry years, or different performance early in the model compared to late. For example, simulating gaged flows that are 10% lower or higher than measurements are less of a concern than simulating increases in water flows when historical data show streamflow declines.

A core element of the calibration process has been to review model results in consideration of the experience of those who manage water in Nebraska. It has been important that the model results make sense and provide answers to the questions the Sponsors have asked.

Professional judgments also are informed by an array of quality assurance and quality control efforts.

3.7 Summary

The model design is intended to provide a reasonably complete and representative quantification of the water budget of the study area, and the design allows for simulation of how that water budget is expected to change if there are future changes in water supply, water use and/or water management.

Ultimately, the water source for the water budget is precipitation, but it is how that precipitation moves over the landscape, through streams, into the aquifer, and supplies water users that require sophisticated tracking methods to analyze the effects of water management. The conceptual hydrologic model of the study area identifies that irrigation is the main factor that modifies the regional water budget, the Platte River and associated canals is the main factor in supplying surface water to the irrigated lands, and the Ogallala and alluvial aquifers are the main sources of groundwater supplies. Three different models are necessary to capture the entire water budget within the Central Platte River Basin; these include a watershed model to capture the land/soil water budget, a surface water operations model to account for storage and diversions of surface water, and a groundwater model to account for aquifer response and groundwater pumping. The models are documented in Section 5, Section 6 and Section 7 respectively; their integrated calibration is presented in Section 8.