APPENDIX F

Evaluation of Methods of Groundwater Operational Yield Analysis,
(RMC, March 2015)

DRAFT Technical Memorandum

City of Modesto - Groundwater Operational Yield

Subject:	**Evaluation of Methods for Groundwater Operational Yield Analysis**
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This Technical Memorandum (TM) is organized by the following sections:

- Background and Objectives
- Overview of Operational Yield Methods
- Methodology Evaluation
- Findings and Recommendations

1 Background and Objectives

The City of Modesto (City) is interested in updating their 2007 groundwater operational yield analysis that was prepared as part of their 2005 Urban Water Management Plan. The operational yield analysis estimated the amount of groundwater that can safely be extracted from the Modesto Groundwater Subbasin without causing adverse impacts and is attributable to the City's water service area. This TM has been prepared to evaluate potential methods for updating this yield analysis for inclusion in the City's upcoming Water Master Plan Update and 2015 Urban Water Management Plan. The objectives for this evaluation are to:

- Research and summarize industry-standard methods for calculating groundwater operational yield estimation;
- Evaluate and rank the various methods (including keeping and reusing the existing operational yield analysis); and
- Recommend an approach for operational yield estimation and provide a cost estimate for such work.

2 Overview of Operational Yield Methods

Operational yield, which can also be thought of as the amount of groundwater supply available for extraction and use within a specified area, can be calculated using a variety of methods. Definitions for operational yield, sustainable yield, and safe yield were developed for the City during the 2005 UWMP development[1] and are included herein:

> **Operational Yield** – is a volume or quantity (typically in acre-feet) of local groundwater withdrawn on an annual average basis from a pre-defined area (i.e. sphere of influence) that does not exceed the long-term annual average recharge rate of the local aquifer(s) from which the groundwater is being pumped. An individual agency's proportionate share of the calculated operational yield can be

[1] 2007 Memo: FINAL – Discussion on Operational Yield for the 2005 Urban Water Management Plan. February 1, 2007.

determined a number of ways. Two examples include basing the yield on factors such as population or acres served, or on the quantity of groundwater pumped compared to the total operational yield available for extraction.

Sustainable Yield – is similar to operational yield, but applies to an entire groundwater basin or subbasin and applies to all of the entities pumping from it as a whole, rather than just a localized area and a specific agency.

Safe Yield – is everything defined for sustainable yield, but also includes other considerations beyond just a quantity of water extracted or recharged, such as its quality and potential surface subsidence issues. Safe yield can be defined as the maximum amount of water that can be pumped without creating any long-term undesirable results.

The purpose of this TM is to evaluate and compare methods for developing an updated operational yield estimate for the City of Modesto's contiguous water service area and sphere of influence; therefore, operational yield is the focus rather than sustainable or safe yield estimation.

Through a literature review, Internet search, and surveying of (by phone) a few water agencies within California, it was determined that there are four general categories of methods for developing operational yield. These categories are as follows:

- Comparative analysis
- Data approach
- Model approach
- Hybrid approach

The categories can also be defined by their level of specificity. As you move from comparative analysis through the data approach to modeling – there is a higher and higher degree of information and specificity to the overall groundwater budget estimate and yield estimate (and, correspondingly, with the requisite data required for the analysis and associated costs to conduct). Table 1 describes the various approach methods for calculating groundwater yield and provides examples of where they have been successfully used.

Table 1: Methods to Groundwater Yield Analysis

Approach Methods	Description	Examples of Use
Comparative Analysis	Looks at pumping and current water levels as compared to historical pumping and corresponding water levels.	• 2007 Modesto Operational Yield Analysis • Patterson Groundwater Supply Evaluation
Data Approach	A quantitative analysis of groundwater budgets (including operational yield) using the groundwater budget equation. All inflows and outflows accounted for using simple analytical tools such as spreadsheets for accounting. Also referred to as a "conceptual model".	• Eastern Municipal Water District (Canyon Basin) • Fresno Groundwater Banking Analysis
Modeling Approach	Uses an existing groundwater model to obtain the groundwater budget information and extract operational yield analysis. Model platforms are typically MODFLOW or Integrated Water Flow Model (IWFM).	• Pajaro Valley • Salinas Valley • SF Peninsula (South Westside GW Basin) • Riverside Public Utilities/Western Municipal Water District • Sonoma County Water Agency (Sonoma Valley and Santa Rosa Plain Groundwater Basins)
Hybrid Approach (Model and Data)	Uses a hybrid approach including some analytical, modeling and historical comparison for calibration	• Sacramento Water Forum (North American River and Cosumnes GW Basins) • Kings Basin Eastern Municipal Water District (Hemet-San Jacinto Basins)

3 Methods Evaluated

The following section describes the various approach methods in more detail and evaluates them based on the following criteria:

- Data required to conduct the analysis and whether the data are readily available
- Frequency of the method used, specifically northern California
- Challenges to conducting the recommended method
- Resources required to implement the recommended method

3.1 Comparative Analysis

Comparative analyses can be used when extensive groundwater basin characteristics data are not readily available, when a calibrated and verified numerical groundwater flow model does not exist, or when the groundwater basin is not complex. The City completed a comparative analysis of the operational yield in its service area in 2007 to develop an estimate of groundwater supplies for its 2005 Urban Water Management Plan. When it developed this initial groundwater operational yield estimate, the City intended to complete "a more comprehensive, hydro-geological groundwater yield study in the upcoming fiscal year where more resources can be devoted to the task of quantifying the City's groundwater operational yield."

The City's initial operational yield estimate was calculated based on historical groundwater pumping rates, response changes in groundwater elevations, and local hydrogeology. Historically, the City's supply was solely dependent on groundwater, and prior to 1995 (when surface water supplies were brought online), a cone of depression had formed under the City. When surface water deliveries began in 1995, groundwater elevations began to rise, correcting the temporary overdraft conditions. Based on these pumping-response data, the City selected a minimum groundwater elevation of 40 feet above sea level (ASL) in its 2007 analysis as the lowest elevation the City would allow groundwater to reach. By establishing this minimum allowable groundwater elevation, the City was able to estimate a conservative operational yield and associated groundwater pumping volume that could be utilized without resulting in overdraft conditions. An update to this analysis can be conducted using groundwater pumping and elevation data obtained since 2005 along with new hydrogeologic information incorporated into the USGS' recent model update.

Data required for a comparative analysis includes, at a minimum, the current rate of extraction and corresponding groundwater levels, along with the historical rate of extraction and groundwater levels. For the City's 2007 analysis, SCADA information was used to determine the annual groundwater extractions from the Modesto, Turlock and Delta-Mendota Subbasins. In addition to the use of empirical data for a comparative analysis, criteria must be set for an allowable minimum groundwater elevation. This minimum groundwater elevation must establish a conservative operational yield that ensures the associated groundwater pumping should not result in an overdraft condition. In order to set an appropriate threshold, data regarding basin trends, such as the existence of cones of depression and at what corresponding groundwater elevations induced, must be obtained. Typically, this information can be found within the California Groundwater Bulletin 118 for the specific basin or subbasins. By plotting groundwater extractions as compared to groundwater levels, a groundwater decline rate can be extrapolated from the slope of the line imposed on the data points. The slope of the line corresponds to a rate of groundwater extracted over the area of interest for the operational yield, and is the estimated operational yield factor. Using the minimum allowable groundwater elevation, in conjunction with the operational yield factor, provides the associated operational groundwater yield.

The comparative analysis is the least sophisticated method of determining operational yield; however, it is an appropriate method to use in the absence of extensive groundwater basin characteristic information and pumping data. Calculation of operational yield through this approach does not account for seasonal peak water demands, water quality restrictions, or localized water distribution and pressure issues. It also does not provide information related to growth, so the sophistication of the analysis and outputs are more limited than with a data, modeling or hybrid approach. While a comparative analysis similar to that conducted in 2007 could be used for updating the City's operational yield estimate, more extensive groundwater information has become available over the last eight years to support a more complex data, modeling, or hybrid approach. These new data include additional pumping and groundwater elevation data (since 2005 and including the last three years of groundwater basin drought response) water quality data, subsidence monitoring, updated hydrogeologic data (developed for inclusion in the update to the USGS MODFLOW model) and water budget information. These data will help refine the previously estimated operational yield value because more information is known regarding the stability of the basin and the changes in groundwater elevations relative to changing hydrologic conditions.

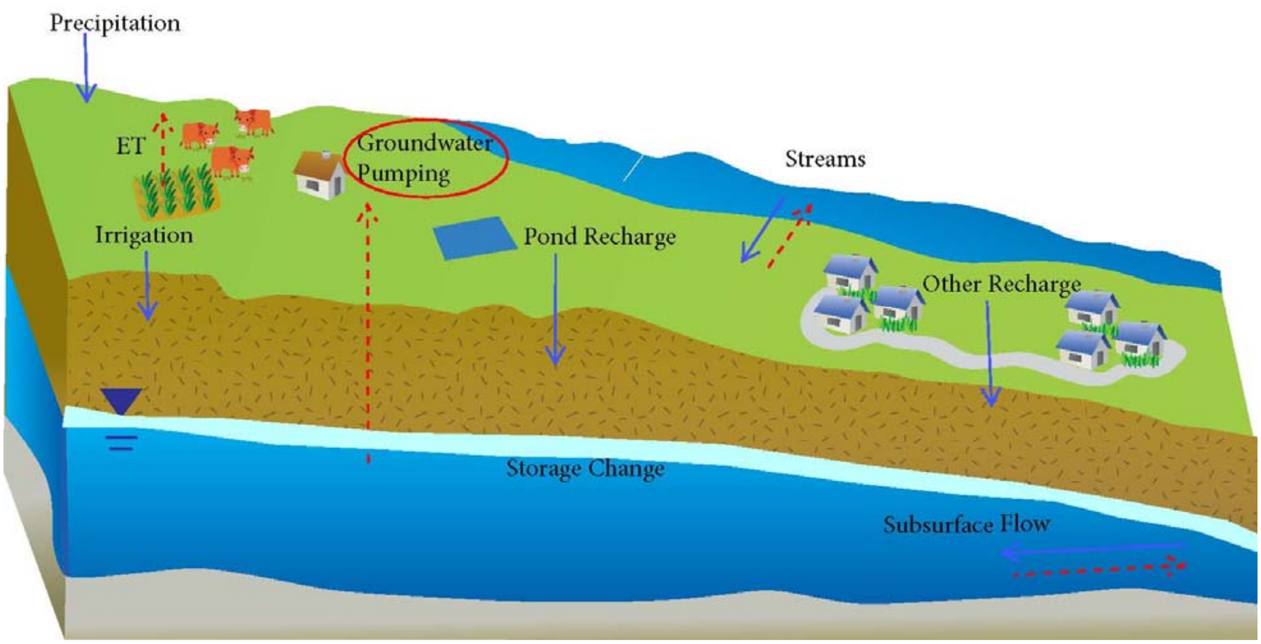
3.2 Data Approach

A data approach can be used when a detailed numerical groundwater flow model is not available for the basin. Compared to the other methods discussed herein, a data approach is more sophisticated than a comparative analysis (as it utilizes numerical representations of water budget components), but is typically less sophisticated than modeling and hybrid approaches discussed below. With a data approach, the analytical results will have a higher degree of accuracy, confidence and defensibility – similar to modeling and hybrid approaches, but will lack the operational flexibility and applicability to specific fine-grained areas. Similar to the relative level of sophistication of this approach, the data approach will be more costly to implement than a comparative analysis, but will be less costly (and less time-intensive) than a modeling or hybrid approach.

To estimate operational yield using a data approach, one must first understand the groundwater budget for the groundwater basin or localized area of interest, thus developing what is known as a "conceptual model" of the groundwater basin. DWR's Bulletin 118 (DWR, 2003) defines groundwater budgets as "an analysis of a groundwater basin's inflows and outflows to determine the change in groundwater storage," which is key information for sustainable groundwater management.

An example of inflow and outflow components which make up a groundwater budget for a typical aquifer system are shown in Figure 1.

Figure 1: Example Groundwater Budget Schematic



Groundwater budgets are estimated using the following equation:

$$\textbf{Inflow (I) – Outflow (O) = Storage Change } (\Delta S)$$

Inflow is calculated by the following:

$$\textbf{Inflow (I)} = I_{PRCP} + I_{IRR} + I_{STR} + I_{SUB} + I_{AR}$$

where:

- I_{PRCP} = Recharge from precipitation
- I_{IRR} = Recharge from irrigation
- I_{STR} = Groundwater inflow from stream
- I_{SUB} = Subsurface inflow/boundary flow
- I_{AR} = Artificial/other recharge

Outflow is calculated by the following:

$$\textbf{Outflow (O)} = O_{PUMP} + O_{SUB} + O_{STR} + O_{ET}$$

where:

- O_{PUMP} = Groundwater pumping (the operational yield estimate being derived)
- O_{SUB} = Subsurface outflow
- O_{STR} = Groundwater outflow to stream
- O_{ET} = Evapotranspiration (ET) by phreatophytes/other outflow

The resulting storage change from the difference in inflows and outflows can also be thought of as the change in volume of groundwater in the saturated zone as indicated by changes in groundwater levels. By defining and understanding all the input and outputs to and from the groundwater basin, and evaluating the resultant long-term groundwater basin storage changes (as reflected in long-term groundwater level changes), one can derive the total groundwater pumping quantity to set as the appropriate operational yield and thereby balance the equation (to show, on average, no long-term groundwater level declines or increases).

There are numerous challenges in estimating the components of the groundwater budget. Some of the more challenging parameters to estimate are as follows:

Boundary Conditions. The Modesto and Turlock groundwater subbasins are just that, interconnected groundwater areas with no discernable groundwater no-flow boundary (such as defines a groundwater basin). Without barriers to flow at the boundaries of the subbasin, conditions within the basin can be affected by inflow from or outflow to neighbor subbasin operations in response to changing conditions (i.e. pumping) outside of the area of study. Additionally, representing the influence of hydrologic boundaries such as the Tuolumne River (and associated changes in river head) on the study area may be lost in the broader scale of the analysis.

Subsurface Flow. Without distinct flow boundaries, subsurface flow into and out of the subbasin is challenging to account for accurately, and subbasin extraction can have out-of-basin effects. If the operational yield is not conservative enough, groundwater levels in neighboring subbasins could have detrimental impacts and result in an unreasonable estimate of available groundwater resources.

Pumping/Extraction. For the City's previous (2007) yield analysis, SCADA data were relied upon to provide the estimate of groundwater pumping within the area of interest. While the City wells are metered and monitored, there are numerous private domestic and agricultural wells that have unknown locations and undocumented pumping practices. While estimates can be developed using Census data assumptions and land use data for irrigation estimates, it is difficult to estimate the total pumping within the basin with a high-degree of accuracy.

Inflow/Outflow to Surface Waters. Surface water courses vary in flow throughout the year which corresponds to a change in the amount of groundwater inflow and outflow to streams. Without a network of measurements across seasonal and year-types, measuring surface water inflow and outflow to the groundwater basin is also difficult to estimate accurately.

Table 2 summarizes the data elements and their corresponding budget equation component required to develop an overall groundwater budget to allow extraction of the appropriate groundwater pumping estimate.

Past studies may contain data or analyses that can support the development of the groundwater budget or may contain groundwater budgets that were developed previously. In addition to past studies, sources of information to obtain groundwater budget elements may include the following:

- DWR Studies/Reports
    - Bulletin 118
    - California Water Plan
    - Detailed Analysis Units (DAUs)
- Local Agencies, Cities and Counties
- Groundwater Model Reports
    - DWR C2VSim Model
    - USGS CVHM Model
    - Regional and Local Models
- USGS Scientific Investigation Reports and Circulars

- California Division of Mines and Geology
- Universities/Academic Organizations
- Professional Organizations (i.e. Groundwater Resources Association of California)
- Non-Governmental Organizations (NGOs)

For more information on developing groundwater budget components, the following references provide useful context:

- DWR's Bulletin 118 (DWR, 2003)
- USGS Circular 1186, "Sustainability of Groundwater Resources" (Alley W.M., Reilly T.E., Franke O.L., 1999)
- USGS Circular 1308, "Water Budgets: Foundations for Effective Water-Resources and Environmental Management" (Healy, R.W., Winter, T.C., LaBaugh, J.W., and Franke, O.L., 2007)
- *Estimating Groundwater Budget* by Richard W. Healy (Healy, 2010)
- The National Research Flagship of Australia's report "Recharge and Discharge Estimation in Data Poor Areas" (Leaney F, Crosbie R, O'Grady A, Jolly I, Gow L, Davies P, Wilford J and Kilgour P., 2011)

Table 2: Groundwater Budget Data Elements

Groundwater Budget Component	Is this applicable to your area	Data Needed									
		Aquifer Characteristics	GW Level	GW Pumping	Rainfall	Land Use	Surface Water Diversion/ Delivery	Stream/Canal Flow	Stream/Canal Characteristics	Artificial/Other Recharge	Soil Characteristics
Inflow Components (I)											
I_{PRCP}	Recharge from Precipitation				✓	✓					✓
I_{IRR}	Recharge from Irrigation (agriculture and urban)			✓		✓	✓				✓
I_{STR}	Groundwater Inflow from Stream		✓				✓	✓	✓		
I_{SUB}	Subsurface Inflow/Boundary Flow	✓	✓								
I_{AR}	Artificial/Other Recharge									✓	
Outflow Components (O)											
O_{PUMP}	Groundwater Pumping			✓							
O_{SUB}	Subsurface Outflow	✓	✓								
O_{STR}	Groundwater Outflow to Stream		✓				✓	✓	✓		
O_{ET}	ET/Other Outflow		✓			✓					
Storage Change (ΔS)											
ΔS	Change in Storage	✓	✓								

3.3 Modeling Approach

Some groundwater basins in California already have numerical groundwater models developed. If such a model is available, it can be used to develop a groundwater budget and hence an operational yield estimate. Additionally, the model can be used to evaluate changes to this operational yield value under a variety of hydrologic conditions to provide either a more conservative average or range of values to be used. If the numerical model report includes a groundwater budget table and the boundary of the model can be matched with the boundary of the specific area being evaluated for the operational yield evaluation, the model results can be used directly either with or without modification or updates to the existing model. If a groundwater budget table is not included in the model documentation, post-processing of model results must be conducted to develop the groundwater budget.

Compared to the other methods discussed in this TM, a modeling approach is more sophisticated than comparative analysis and data approaches, but less sophisticated than a hybrid approach, which includes extensive data evaluation and comparison in addition to modeling. As noted in the Data Approach section, the output of a modeling analysis will have a high degree of accuracy, confidence and defensibility. Additionally, modeling approaches provide the highest degree of operational flexibility and can be widely applied both to regional and specific fine-grained areas. However, a modeling approach, along with the hybrid approach, is the most costly and time-consuming approach to implement. Part of this cost is the staff time required to bring staff up-to-date on the model structure and interfaces, and the time required to understand the model's sensitivity to various parameters, including the hydrologic impacts of microstratigraphy.

Popular numerical groundwater models include the following:

IWFM – Includes a Groundwater Budget table providing a time series of budget components for the simulation period, by model subregion. The Z-Budget postprocessor extracts water budget components out of model results for any area of the model.

MODFLOW - Zone Budget postprocessor extracts water budget components out of the model results.

MicroFEM - Water Balance postprocessor extracts water budget components out of the model results

The City anticipates having access in the near future to the U.S. Geological Survey (USGS) Modesto Regional MODFLOW model. This model covers most of the Modesto and Turlock subbasins plus small areas of the East San Joaquin, Delta-Mendota and Merced groundwater subbasins. The Modesto Regional Model was recently updated, therefore the Zone Budget would be an appropriate approach, using the postprocessing tool for this assessment. The model boundary is the basin, however, the model can be discretized to replicate the specific area of the basin (the City's contiguous water service area and sphere of influence) which is the focus of the operational yield estimate.

3.4 Hybrid Approach

A hybrid approach to developing yield estimates utilizes a combination of numerical and analytical methods to estimate yield. Compared to the other methods discussed in this TM, the hybrid approach is the most sophisticated method evaluated. This method provides the highest degree of flexibility, accuracy, and applicability, but also bears the greatest cost of all the methods described herein.

For example, such an approach would use an existing groundwater model to provide larger, basin-wide values for the various water balance components, and then use an analytical approach to apply this on a regional or local basis. This is one method for using more readily-available numerical data from an existing, regional groundwater model, without the associated costs of discretizing the elements in the area of interest into a finer grid mesh to achieve more locally-based results. The scaled-down localized results can be compared to historical data to 'truth-check' the results for reasonableness. This approach can also be used where a numerical model is available but out of date. Rather than update and recalibrate the entire groundwater model, the existing model is used with appropriate assumptions and the results cross-checked against existing historical data for accuracy. A second version of this method is to use the larger regional model to establish boundary conditions for a second, discretized model used to simulate local conditions.

3.5 Summary of Approach Methods

A summary of evaluation criteria are shown in Table 3. A flow chart describing a logic process for the selection of alternative methods is presented in Figure 2. Methods were ranked based on criteria listed in Table 3. The highest ranking method (Rank = 1) is the hybrid approach, which combines modeling with data analysis and comparison of historical data.

Figure 2: Process Flow for Selection of Method for Groundwater Budget Development

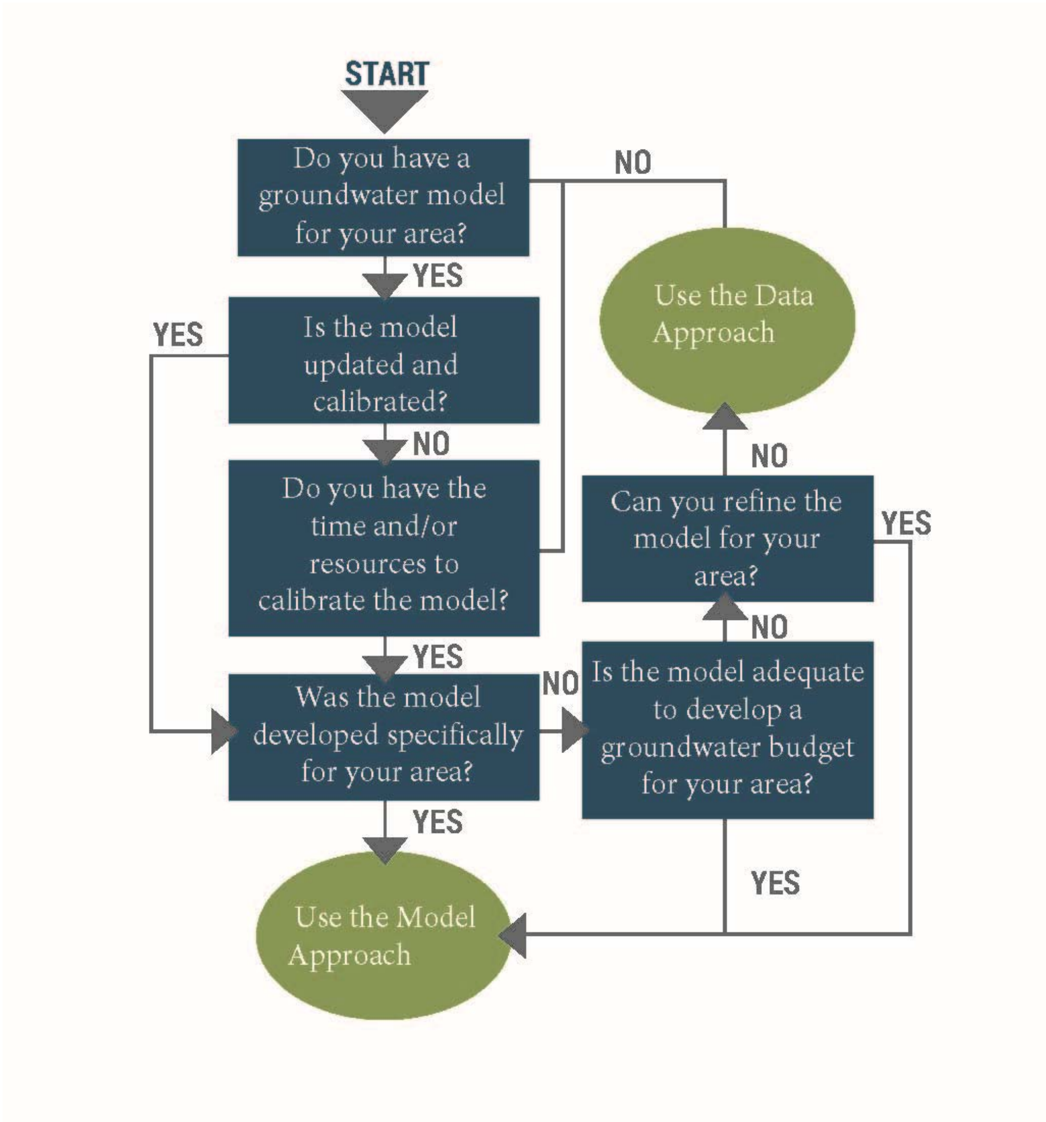


Table 3: Evaluation of Approaches to Operational Yield Analysis

Approach Method	Data Required to Conduct the Analysis and Availability	Frequency of Use of Method	Challenges	Resources Needed to Implement	Ranking
Comparative Analysis	• Updated pumping estimate (present and historical) • Updated water levels (present and historical) **AVAILABLE**	Used when data are limited and no model is available	Not representative of complex systems. Assumes data points are under normal hydrological conditions.	Staff level resource to identify data sources and conduct analysis, senior level review	4
Data Approach	• Soil • Topography • Hydrology • Climate • Land Use • Basic aquifer characteristics • Groundwater elevation data • Groundwater extraction data **MOSTLY AVAILABLE**	Common in non-complex basins with available data	• Extensive data needs • Complex calculations and hard to update as new data are developed • Challenging to capture underflow accurately • No functionality to run scenarios to adjust parameters or conduct sensitivity analysis (not dynamic) • Hard to limit to a localized area/portion of a groundwater basin	Staff level resource to identify data sources and conduct analysis, senior level review	3
Modeling Approach	• Existing numerical model • Post-processing tool **AVAILABLE**	Most common if a numerical groundwater model is available	• Model data needs to be current/representative • Model updates can require extensive data and time to incorporate appropriately	Requires staff level with modeling knowledge to run post-processing software to extract groundwater budget elements and senior level review	2
Hybrid Approach	• Partial data set from Data Method • Existing numerical model **MOST AVAILABLE**	Relatively frequent where a numerical model is out-of-date	Requires both data analysis and modeling components. Also requires historical information for comparative analysis.	Same as Modeling Approach	1

4 Findings and Recommendations

Findings from research indicate there are four categories of industry-standard operational yield estimation methods. These categories are:

- Comparative Analysis
- Data Approach
- Model Approach
- Hybrid Approach

When an existing numerical groundwater model is available for a groundwater basin, the most common method for yield development is to utilize the groundwater model. Extracting groundwater budget information from a model can be done using post-processing software, particularly with respect to modifying the modeled study area to better match the localized study area of concern. Utilizing a Modeling Approach allows for flexibility in running various pumping scenarios, modifying groundwater budget variables in the model to determine the sensitivity to parameters, and taking a real-time look at how various pumping ranges effect groundwater flow conditions such as subsurface flow, groundwater levels, etc.

It is recommended that the City complete their operational yield analysis using either the Modeling or Hybrid Approaches, depending on the level of effort budgeted for this evaluation and the availability of the USGS MODFLOW model. The basis for this selection is that the City has access to a recently updated and re-released USGS MODFLOW model. The City can utilize the water budget information that has been developed by the USGS, a third party which has been subject to rigorous quality assurance and quality control, and which will provide the most comprehensive look at the data input parameters available. These data can then be used with an analytical method to downscale and better match the boundary of the Modesto Sphere of Influence (or other study area), or the model grid itself can be discretized to provide more refined estimates of water balance components for the proposed study area, or both.

Additionally, by using the USGS MODFLOW model, the City can run multiple pumping scenarios to determine the appropriate operational yield threshold, and also evaluate the potential impacts of pumping certain well clusters more or less, as it relates to the potential creation of localized cones of depression. After running scenarios and extracting the operational yield estimate, the City can then compare the model outputs with historical water levels and pumpage, thus conducting a hybrid analysis as a final check. In summary, the tasks for this hybrid approach and their level of effort is shown in Table 4. However, it should be mentioned that what neither of these methods addresses is the issue of delivered groundwater quality, and the potential water quality impacts which would result from these various groundwater management scenarios.

Table 4: Estimated Level of Effort to Conduct Hybrid Approach Yield Analysis

Task	Description	Labor Estimate
1.Data Collection	Obtain model and determine appropriate post-processing software	$10,000
2. Run Scenarios	Determine scenarios to model and run scenarios, generating output information	$45,000
3. Scenario Analysis and Recommendations	Compare scenarios and evaluate against criteria such as water levels, underflow, etc. Rank scenarios and recommend operational yield.	$15,000
4. Historical Comparison	Compare results and recommended yield along with model output water levels to historical water levels and corresponding pumpage.	$15,000
5. Summarize Findings	Summarize findings and recommendations in a TM.	$15,000
	Total Estimated Fee:	***$100,000***