HRS

THE COLORADO WATER CONSERVATION BOARD
AND
OFFICE OF THE COLORADO STATE ENGINEER

SENATE BILL 96-153 PHASE 1 REPORT
AND
PHASE 2 SCOPE OF WORK

Prepared for

COLORADO WATER CONSERVATION BOARD

November 13, 1996
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CONSULTANTS IN
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November 13, 1996

Mr. Will Burt, P.E.
State Engineer's Office
1313 Sherman St. Room 818
Denver, Colorado 80203

Mr. Michael Serlet, P.E.
Colorado Water Conservation Board
1313 Sherman St., Room 721
Denver, Colorado 80203

Re: S.B 96-153 - Phase 1 Report

Dear Messrs. Burt and Serlet,

Attached is the S.B. 96-153 Phase 1 Report. We have prepared this report as a part of our S.B. 96-153 Phase 1 work. After your review of the report please call us with any comments or questions you may have. We look forward to presenting this report to the Water Conservation Board later this month.

Very truly yours,

HRS WATER CONSULTANTS, INC.

Mark R. Palumbo
Vice President

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1.0 Purpose of the Phase 1 Study

Senate Bill 96-153 authorizes a study on the economic life of the Denver Basin aquifers. The S.B. 96-153 work is divided into Phase 1 and Phase 2. At the conclusion of a competitive proposal and interview process, HRS Water Consultants, Inc. was awarded the contract to perform the Phase 1 work. S.B. 96-153 states that Phase 1 may include: 1) a survey of the adequacy of groundwater flow models; 2) an analysis of the availability of well pumping data; 3) the identification of key questions to be resolved by the Phase 2 analysis; and 4) the development of the Phase 2 work plan.

Discussions concerning the economic life of the Denver Basin aquifers have occurred for more than 20 years. Denver Basin aquifer hydrogeologists realize that production from the Denver Basin aquifer wells will decline over time due to a reduction of the aquifers' saturated thickness caused by pumping. If a certain population is served with Denver Basin aquifer groundwater, the cost of delivering the groundwater will increase as more water wells are required to meet the population's water demand. An unknown at this time is how water well production rates will decline and how the cost of Denver Basin aquifer groundwater production will increase over time. The work in S.B. 96-153 is meant to address these two very important questions.

Determining the economic life of the Denver Basin aquifers is a complicated problem. Analysis of the problem involves: groundwater hydrology, hydrogeology, geology, water well hydraulics, analytical and numerical groundwater flow modeling, borehole geophysics, current and future Denver Basin aquifer groundwater demands, population projections, economic analysis, Colorado Water law, and knowledge of water well installation and equipping.

The analysis of production and drawdown in a Denver Basin aquifer well is made more complicated by the fact that aquifers are composed of interbedded layers of sandstone, siltstone and shale. Denver Basin aquifer water wells are constructed such that well screens are placed adjacent to the saturated sandstone/siltstone layers. An aquifer with ten 20-foot sandstone layers separated by shale layers is not the same as a continuous 200-foot thick sandstone aquifer. A primary difference between these two aquifers is the amount of available drawdown which can be placed on the aquifer materials under unconfined conditions. The maximum change in hydraulic head (drawdown) which can be placed on a 20-foot thick sandstone layer is 20 feet. A 200-foot drawdown can be placed on the 200-foot aquifer. A larger amount of groundwater production will be available from the 200-foot aquifer.

An additional issue is nonlinearity of specific capacity in an unconfined layered aquifer. Under confined aquifer conditions, specific capacity is constant and there is a linear relationship between pumping rate and drawdown. When unconfined conditions occur specific capacity is no longer constant and the relationship between pumping rate and drawdown is nonlinear. When the groundwater level is below the base of a layer, unconfined sandstone layers will drain into a well independently of the pumping water level in the well. Flow into the well from unconfined layers will be based on the hydraulic conductivity and the hydraulic gradient of the sandstone layers.

The economic life of the aquifers should be analyzed as an aquifer drawdown problem where the relationships among aquifer drawdown, the pumping water level in a well, and production from a Denver Basin aquifer well are all taken into account. The problem can be stated as follows: How does production from the Denver Basin aquifers change in response to reduced saturated thickness and lower pumping water levels? Well pumping rates are important because they are the measure of an aquifer's production. Additionally, the costs of well installation, operation and maintenance over time to maintain aquifer production will be included in the economic analysis.

2.0 Key Study Questions

2.1 Meeting with the State Engineer's Office

On October 16, 1996, a meeting was held with personnel from the State Engineer's Office (SEO) to discuss the Senate Bill 96-153 work. Following the direction of Senate Bill 96-153 the key questions for the Phase 2 study were agreed upon at this meeting. The key questions are:

1. How does the pumping water level in a Denver Basin aquifer well decline over time?
2. How do the declines in pumping water levels in Denver Basin aquifer wells effect groundwater production rates over time?
3. What is the cost of maintaining groundwater production levels over time?

3.0 Availability of Well Pumping Data

3.1. Denver Basin Aquifer Groundwater Production Data

It is clear that better information on Denver Basin aquifer groundwater production would be helpful in the evaluation of the economic life issue. Owners and operators of fee wells are required to maintain groundwater production records. It is not required that these records be submitted to the SEO unless they are requested. Previous efforts by the State Engineer's Office to obtain Denver Basin aquifer groundwater production information have not been successful. Some current information on municipal production from the Denver Basin aquifers was obtained as a part of the Metro Water Supply Investigation. Arapahoe and Douglas Counties have assembled estimates of municipal Denver Basin aquifer groundwater production. The estimate of municipal well production from the Denver Basin aquifers in Douglas and Arapahoe Counties is 22,000 af/yr. Gathering and compiling data from all fee wells is well beyond the scope of this project. The study will rely on production estimates developed by previous investigators or current production rates at individual wells.

Previous work by Robson (1987) and others in the Denver Basin has indicated that estimates of groundwater production are a source of error in the analysis of the Basin's groundwater resources. Robson (1987) states that the Denver Basin aquifer production estimates used in his modeling work are accurate within a range of plus or minus 20 to 30 percent. In his 1987 report, he determined that for the period 1958 to 1978, that total pumping in the Denver Basin aquifers was equal to 3.5 to 4.5 times municipal pumping. It is not known if this factor between municipal pumping and total pumping is currently accurate.

In addition to annual pumping data, it would also be useful to have more data on: maximum pumping rates, monthly production volumes, static water level measurements at various times, pumping water level measurements, and aquifer properties of transmissivity, hydraulic conductivity, and storage coefficient.

Groundwater production and hydrogeologic data have been surveyed in this Phase 1 study to determine whether or not the results of previous modeling work can be considered as valid for the purpose of evaluating the economic life of the aquifers. The conclusions of this survey are that a limited amount of data is available on Denver Basin aquifer well pumping and that the accuracy of existing estimates is questionable. The derivation of new production estimates is beyond the scope of this study. Well production estimates used by Robson (1987) and Banta (1989) at specific aquifer locations will be analyzed. Well production rates used in the economic analysis may be altered to reflect site-specific aquifer conditions.

3.2 Groundwater Level Data

Some owners of fee wells maintain static and pumping water level records since this is a method of tracking well efficiency and expected water well work. It should be possible to obtain some of this data if required in Phase 2. Groundwater level data is seldom available for domestic wells except when the wells are drilled or replaced. The best information on Denver Basin aquifer groundwater levels is compiled by the State Engineer's Office. Groundwater level data has been obtained and published on an annual basis since 1987.

4.0 Adequacy of Groundwater Flow Models

Economic analysis of the effective life of the Denver Basin aquifers must be done under actual present conditions and our best estimate of expected future conditions. Estimates of the required lift of water to the ground surface should be based on expected actual groundwater levels in the aquifers and in the wells. Estimates of future water levels can be developed by simulating the flow conditions in the aquifer in the future. To be accurate, such a simulation should take into account the physical processes affecting groundwater flow. The processes of greatest importance in this discussion of the existing simulation models of the Denver Basin are: precipitation recharge, leakage between the aquifers, leakage to and from surface water bodies, horizontal flow within the aquifers, and confined and unconfined storage.

At present, static groundwater levels in the Denver, Arapahoe, and Laramie-Fox Hills aquifers are above the tops of the aquifers over most of the basin. Groundwater stored under pressure is called artesian or confined storage. It has been estimated that the water in confined storage in the Denver Basin is less than 0.1 percent of the total amount of recoverable storage. After this confined storage has been drained, the groundwater level is at the top of the aquifer and additional withdrawals result in actual dewatering of the pore spaces in the aquifer. Groundwater stored in these pore spaces is called unconfined storage and makes up most of the aquifer storage. Since use of the confined storage may result in groundwater level changes of hundreds of feet, this storage can be very important in an analysis of the actual expected groundwater levels.

4.1 State Engineer's Office Denver Basin Groundwater Flow Models

The State Engineer's Office groundwater models are described in the report "Denver Basin Ground Water Model Report", by the Colorado Division of Water Resources, November 15, 1985, Technical Appendix C. These models are intended to be used for a very specific purpose: definition of the location of nontributary groundwater in the Denver Basin bedrock aquifers under the conditions of Senate Bill 5. In this modeling effort, the major aquifers in the

Denver basin were each treated individually. The models are set up to be run with the MODFLOW model (McDonald-Harbaugh, 1988).

Under the Senate Bill 5 requirements, calculation of depletion for the purpose of definition of the location of nontributary groundwater is done assuming that the water level in the aquifer has been lowered to the top of the aquifer. Thus these models are designed as change models with initial groundwater level in each aquifer as a flat surface. Any pumping produces groundwater movement in the aquifer and induces recharge from the surface water streams. This depletion in surface water flow is tracked in analysis of the model results and used to determine stream depletion in response to pumping.

The models are required by Senate Bill 5 to ignore water in confined storage in the aquifers and cannot calculate actual expected changes in water level in the aquifers. As such, they are unsuited for use in an analysis of the economic life of the aquifers. Horizontal flow within the aquifers and vertical leakage between the aquifers are calculated by these models. In developing these models, extensive geologic and hydrologic data were gathered and compiled. This data will be of use in the Phase 2 analysis for this project.

4.2 Robson's Denver Basin Model

A modeling project performed by S. G. Robson of the U.S.G.S. is described in the report entitled "Bedrock Aquifers in the Denver Basin, Colorado - A Quantitative Water-Resources Appraisal", U.S.G.S Professional Paper 1257, 1987. In this project, a single groundwater model of the four major Denver Basin aquifers was developed, calibrated, and used for simulations of groundwater level changes expected in response to several water demand scenarios. The model code was developed by Trescott and Larson (1975) and S.P. Larson (1976).

This is a calibrated hydraulic head model and accounts for: water in both confined and unconfined storage, leakage between the aquifers in response to changes in groundwater levels in the various aquifers, induced infiltration from streams, and recharge from precipitation.

Simulations were performed for a history-matching period from 1958 to 1978 and a prediction period from 1979 to 2050. Predicted groundwater levels were calculated under several water demand conditions:

1. FULL - Pumping based on projected water supply requirements for the Denver Metro area
2. HALF - One-half of the FULL pumping rates
3. STDY - pumping is assumed to be remain constant after 1983, the most conservative estimate.

The methods used in this modeling effort are appropriate for determining the regional groundwater level declines in each aquifer as a result of pumping. The model calculates groundwater levels in response to the major physical processes controlling groundwater flow in the basin. The model grid setup is rather coarse with large model cells, making it difficult to get results for specific well sites.

We have contacted Mr. Robson concerning availability of the model setup and results. Printouts of the results from the various simulations discussed in the report exist and could be used to pick groundwater levels at various sites for further analysis. The exact model code used for the simulations may be available only on printout. Since codes changes may have been made in this model it may be difficult to rerun it to produce additional results for different pumping scenarios.

4.3 Banta's Denver Basin Model

The analyses performed by Robson formed the basis for later work by E. R. Banta (Banta, E. R., 1989, Hydrologic Effects of Pumpage From the Denver basin Bedrock Aquifers of Northern El Paso County, Colorado, U.S.G.S. Water Resources Investigation Report 88-4033). The Trescott-Larson model was also used in this project, and the basic setup is quite similar to that used by Robson, though the finite difference grid has been revised in much of the modeled area to give better resolution from a finer grid. Additional changes have been made to more accurately simulate interactions between surface water and groundwater in the southern part of the basin. The smaller grid size over much of the basin makes this a better choice for use as a basis for estimation of expected groundwater levels in the aquifer.

As in the Robson model, several simulations were performed to calculate groundwater level changes in response to different levels of groundwater use. For our purposes, the most useful simulations will likely be:

1. SIMBASE - Pumping in southern part of basin constant at 1985 level. Pumping in northern part of basin as Robson FULL simulation
2. SIMGRO - Pumping in southern part of basin increases in response to growing population. Pumping in northern part of basin as Robson FULL simulation

We have contacted Mr. Banta regarding availability of the model code, setup, and results. FORTRAN code for the Trescott-Larson model as used for the steady state and transient simulations is available on disk, though it is set up for use on a Prime computer. Changes would likely be required for this model to be compiled and used on a PC. Steady state input and output files and calibrated heads are available on disk. Input, output, and heads are available on disk for the SIMBASE simulation. It may be difficult to obtain input and results for the other simulations on disk or as printout.

4.4 Schenk's Denver Basin Model

The modeling work by Banta was used as the basis for a modeling project by J. Schenk at the Colorado School of Mines. Banta's model was converted for use with the MODFLOW code and used in simulation of interactions between the bedrock aquifers and surface streams (Schenk, J. and E. Poeter, 1990, RIVINT, An Improved Code for Simulating Surface/Groundwater Interactions with MODFLOW). The goal of this project was development of an alternate program package for calculation of the interactions between surface water and groundwater. As such, limited pumping simulations were performed.

This model implementation has the advantage that it uses a groundwater model code which is currently available and accepted by the modeling community. The MODFLOW code is available for PC's and is well understood and widely used. Unfortunately, the results of simulations performed for this project probably do not directly address the problems of interest here. Simulations were performed for pumping rates similar to those used by Banta, but the simulations were only performed for the 40-year period from 1958 to 1998. As such, the existing simulation results will not help in estimation of the expected economic life of the aquifers.

We have contacted Ms. Schenk about availability and use of this model. The model setup as used in the project is available. The simulations performed by Banta were not reproduced. Some changes may be required in the model setup for it to accurately reproduce Banta's results. Since the goal of the project was development of a new package to calculate interactions between rivers and the bedrock aquifers, the original river setup may not be available.

4.5 Jaunarajs' Model

The model developed by Schenk for more realistic simulation of interactions between surface water and groundwater was used as the basis for pumping simulations during drought periods by S. R. Jaunarajs (Jaunarajs, S. R., 1991, A Modeling Approach for Assessing the Feasibility of Ground-Water Withdrawal from the Denver Basin During Periods of Drought, Colorado School of Mines). This project involved some recalibration of the MODFLOW implementation of the Denver Basin model and 40-year simulations of increased pumping during hypothetical drought cycles.

Due to the simulation period and the pumping stresses, the results of this work are probably not directly applicable to this project. If recalibration of the model is envisioned, the results of this effort should probably be consulted as it represents one method of reaching a better match between observed and calculated heads. Since this model is based on the work of Schenk, it will probably not help in reproducing the results of Banta's simulations.

4.6 Recommendations

The results of Banta's model should be used for estimates of expected regional changes in groundwater levels. The smaller size of the grid cells over much of the basin and the resulting better resolution make this a more desirable model for use in this project. If the results of simulations for appropriate pumping rates are available, it should be possible to use these hydraulic head and drawdown values without the need to rerun the model.

If appropriate results are unavailable for Banta's model, then it may be necessary to either use Robson's results for the simulation most closely matching the projected demand, recreate Banta's results, or rerun a model to derive groundwater level changes for different pumping rates. For recreation of Banta's results and derivation of new results for different pumping rates or different hydrogeologic parameters, we recommend that the version of the model converted to MODFLOW by Schenk be used. This will likely require limited recalibration to the data used by Banta, but the comparative ease of using the MODFLOW model probably outweighs any possible advantages of using the original Trescott-Larson model.

5.0 Phase 2 Scopes Of Work

We have prepared two Phase 2 scopes of work. The first scope is for $30,000. This $30,000 budget matches the budget amount established for Phase 2 work in S.B 96-153. A second scope of work for approximately $33,500 is also presented. The second scope represents additional work which should occur to obtain a more complete study on the Economic Life of the Denver Basin aquifers.

5.1 Phase 2 Scope of Work No. 1

The Phase 2 Scope of Work No. 1 tasks are attached as Table 1. Figure 1 is a scope of work task flow chart. The anticipated cost for the work is $30,000. The five Phase 2 tasks for this scope include:

Task Number

1. Literature Review - Aquifer Layering Effects on Well Production
2. Radial-Flow Correction Analysis
3. Denver Basin Aquifer-Layered Radial Flow Production Analysis
4. Economic Analysis
5. Report

In this Phase 2 work, the results from two production-drawdown analyses will be compared to determine the most accurate method to determine drawdown at a Denver Basin aquifer well. Results of a radial-flow correction to estimate groundwater level in a well based on groundwater level in a model cell performed on output from Banta's model, Task 2 above, will be compared to drawdown results from a layered-radial flow numerical model, Task 3 above. The comparison will be performed on wells from the same location in response to identical pumping stresses. If the pumping stresses at the selected model cells are considered unreasonable, additional simulations will be performed with more appropriate well production rates. The pumping water levels from these simulations would then be used as input to the economic analyses.

It is expected that the layered radial flow model will produce the more accurate results when compared to the radial flow correction analysis. However, if the radial flow correction analysis can produce results comparable to the layered analysis, the study will benefit from an analysis of more aquifers and well locations.

An economic analysis of the Arapahoe aquifer in the northern metro area is complicated by the division of the Arapahoe aquifer into the Upper Arapahoe and the Lower Arapahoe under S. B. 5. Prior to S. B. 5 Arapahoe aquifer wells were completed over the entire aquifer. Robson (1987) and Banta (1989) maintain the Arapahoe aquifer as one aquifer in their models. Therefore, regional groundwater level decline and production information in these United States Geologic Survey reports is not directly applicable to Upper and Lower Arapahoe aquifer well completions.

The following Phase 2 No. 1 scope of work options relate to the Arapahoe aquifer in the northern metro area.

1. Perform the economic analysis on a non-divided Arapahoe aquifer well.
2. Perform an economic analysis on a Upper Arapahoe aquifer well.
3. Perform an economic analysis on a Lower Arapahoe aquifer well.
4. Perform an economic analysis on another aquifer.

Option No. 1 above is described in this scope of work. This option should be considered a preliminary choice which is subject to change. Another option could be selected in Phase 2 of this study.

5.1.1 Literature Review - Aquifer Layering Effects on Well Production

A review of the published scientific literature will be performed to examine articles on the effect of layered aquifers on well production. The purpose of the literature review will be to understand previous work on aquifer layering and well production. A list of the articles reviewed will be included in the Phase 2 report. Additionally, the Literature Review report section will describe the significance of each article to groundwater production in the Denver Basin aquifers. The report should also describe any relevant conclusions.

5.1.2 Radial-Flow Correction Analysis

Robson, Banta and other investigators have performed groundwater flow modeling studies of the Denver Basin aquifers. Regional groundwater flow modeling analysis of the Denver Basin aquifers can provide reasonable estimates on the rate of annual regional groundwater level declines. Previous analyses by Robson, Banta, and others have quantified regional groundwater level declines in response to past and future groundwater production levels. A finite-difference model divides the area of investigation into a model grid with model cells. In this task the previously-calculated regional drawdown in a model cell will be corrected to estimate the groundwater level in a well located in the middle of the model cell.

The drawdown correction will be performed at individual model cells in Banta's model which are representative of an aquifer area. Radial-flow correction analyses may be performed at the following locations: the Dawson aquifer in the southern metro area; the Denver aquifer in the northern metro area, the southern metro area, and south of the Palmer Divide; and the Arapahoe aquifer in the north metro area, the south metro area and south of the Palmer Divide. Corrected drawdown values at the three Arapahoe aquifer locations will be compared to drawdowns calculated at the same three Arapahoe aquifer locations using a layered-radial flow analysis (section 5.1.3). A comparison of the drawdown values will be used to determine whether or not the radial-flow correction analysis can be used to accurately determine Denver Basin aquifer pumping water levels.

The cell-to-well radial flow correction analysis should first be performed on the three Arapahoe aquifer well locations: the northern metro area; the southern metro area; and south of the Palmer Divide. The layered-radial Arapahoe aquifer work described in the following section will then be performed. If the results of the radial-flow correction analysis are significantly different than the results of the layered-radial flow analysis and if an adjustment to the radial flow correction cannot be obtained to accurately reflect the layered-radial flow results, then the decision may be made not to perform the radial flow correction analyses on the other aquifers. If the radial-flow drawdown in the Arapahoe approximates the layered-radial flow drawdown analysis, the radial-flow correction on the Dawson and Denver aquifers will be performed. The pumping groundwater levels from these analyses may be used as input to the economic analyses. It is anticipated that a 50-year production period from 1997 to 2046 will be evaluated.

For each aquifer analysis under this task, the following specific tasks will be performed:

1. Obtain model input and output files from Banta (1989) or another appropriate investigator to determine if simulated drawdown values are available for analysis.
2. Select the specific aquifer area and cell for analysis. The aquifer cell selected for analysis should represent average aquifer conditions for the area of investigation.
3. Obtain data on initial aquifer conditions, pumping stresses, groundwater level and drawdown over the simulation period. Create a hydrograph of drawdown values.
4. Perform the correction for drawdown in the model cell to drawdown in the well and calculate corrected drawdowns and pumping water levels. Create a hydrograph of pumping water level over the stress period.

5.1.3 Denver Basin Aquifer - Layered Radial Flow Production Analysis

Layered radial flow analyses will be performed on three Arapahoe aquifer wells. The Arapahoe aquifer wells will be located in the northern metro area, the southern metro area and south of the Palmer Divide. The geophysical logs for wells at these locations will be examined and the sandstone and shale layers will be coded into a layered radial flow model. Pumping rates and periods identical to the rates and periods used for the wells in the Denver Basin aquifer finite-difference model will be simulated in this layered radial flow analysis. The regional aquifer drawdown will be accounted for in this analysis. Drawdown will be calculated over the same time period as the wells in the radial flow correction model. The layered radial flow analysis may indicate that wells go dry before the end of the analysis period. It is assumed that if actual wells go dry, additional wells will be installed so that production rates can be maintained. As additional wells are installed, withdrawal rates from each well should then be adjusted to the desired total production. In a radial model, this change in wellfield operation can be simulated by a reduction in well discharge to one-half of the original rate and adjustment of boundary conditions to reflect the expected closer well spacing. The model should then be rerun from the beginning of the simulation with two pumping periods such that the well does not go dry and the model transitions to the second stress period with the lower pumping rate. This procedure of dividing the pumping rate in half, adding a stress period, adjusting the boundary conditions, and restarting the simulation may occur again before the end of the simulation period. It is anticipated that a 50-year simulation from 1997 to 2046 will be performed.

If the results from the layered radial flow model are determined to be more accurate than the radial correction flow model analysis, the pumping water levels from the layered radial flow production analysis will be used in the economic analysis. In this case economic analyses will be performed for Arapahoe aquifer wells in the northern metro area, the southern metro area and south of the Palmer Divide. If radial-flow correction analyses are not performed on the Dawson and Denver aquifers, an additional layered radial flow production and economic analysis may be performed on a Denver aquifer well in the southern metro area.

For each aquifer analysis under this task, the following specific tasks will be performed:

1. Select a well within the radial flow correction model cell area.
2. Analyze the well's geophysical well log to evaluate aquifer layering.
3. Determine the well's maximum sustained production rate.
4. Evaluate the aquifer hydraulic conductivity.
5. From the regional groundwater flow model, determine regional annual groundwater level declines.
6. Select an appropriate layered-radial numerical groundwater flow model code.
7. Develop the input files for the model run.
8. Run the model at the same pumping stress as the well in the radial flow correction analysis and over the same pumping period.
9. Analyze results from the model. Create a hydrograph of pumping water level.

10. If required, perform additional model runs with adjusted pumping rates to the end to the stress period.

5.1.4 Economic Analysis

Economic analyses will be performed to determine the cost of Denver Basin aquifer groundwater production. An economic analysis will be performed for each well analysis. The economic analysis will include the capital and operational costs of groundwater production over the simulation period. The expected economic analysis period is 1997 to 2046. Costs related to well installation, pumping equipment, electric power, operation, maintenance, equipment replacement, well design and installation oversight will be included in the economic analysis. The contractor will obtain and document current cost estimates for all capital, operation and maintenance items.

A discount rate, a unit energy cost per Kwh, and an annual energy cost escalation factor will be included in this analysis. An annual inflation factor will be applied to first year costs. A spreadsheet will be prepared to calculate costs over the period. The spreadsheet will include a row for each year. At a minimum the following values should be presented for each year of operation: net present value factor, yield in acre-feet per year, pumping water level, well cost, equipment cost, operation and maintenance costs (pumping costs and O & M fixed costs), total annual cost, annual unit cost per acre foot, and present value cost. Total capital costs and total unit costs on an acre foot basis should be presented in addition to total net present value costs and net present value unit costs on an acre foot basis.

5.1.5 Report

A report will be prepared to document the assumptions, analyses and results of the Phase 2, No. 1 investigations. Graphs and figures should be prepared where applicable to explain the results of the analysis. The report will include a discussion of domestic well production and the potential effects of regional groundwater-level declines on production.

5.1.6 Schedule of Work

The contractor will have 12 weeks to complete the work described as Phase 2 Scope of Work No. 1. The starting date for the work will be the date the contractor signs the contract to perform the work.

5.2 Phase 2 Scope of Work No. 2

A second Phase 2 scope of work has been prepared. Task descriptions for this second scope of work are included on Table 2. This second scope contains additional tasks which are related to Scope of Work No. 1. Scope of work No. 2 expands the layered-radial flow analyses to five additional aquifer locations: the Dawson aquifer in the southern metro area; the Denver aquifer in the northern metro area, the southern metro and south of the Palmer Divide; and the Laramie-Fox Hills aquifer in the southern metro area. For wells at these five locations the pumping groundwater level in the wells will be determined in response to projected long term production rates. The economic analyses as described in 5.1.4 above will be performed on these wells based on the wells' pumping water level and production rates. Phase 2 Scope of Work No. 2 tasks should be completed 15 weeks from the date of the signed contract. The estimated cost for this work is $33,500.

REFERENCES

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Jaunarajs, S. R., 1991, A modeling approach for assessing the feasibility of ground-water withdrawal from the Denver basin during periods of drought, Colorado School of Mines, 102 p.

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Robson, S. G., 1987, Bedrock aquifers in the Denver basin, Colorado - A quantitative water-resources appraisal, U.S.G.S Professional Paper 1257, 73 p.

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Trescott, P.C. and S.P. Larson, 1976, Documentation of finite-difference model for simulation of three-dimensional ground-water flow, supplement to Open-File Report 75-438: U.S.G.S Open-File Report 76-591, 21 p.

Table 1

Colorado Water Conservation Board and The State Engineer's Office
Senate Bill 153 - Economic Life of the Denver Basin Aquifers

HRS Water Consultants, Inc.

November 12, 1996

Phase 2 Scope of Work - No. 1

Tasks

1.0 Literature Review - Aquifer Layering Effects on Well Production

1.1 Perform literature search on aquifer layering effects, review articles and write-up conclusions.

2.0 Radial Flow Correction Analysis

Each of the following subtask will include the following:

- **Select aquifer area and cell for analysis**
- **Create a hydrograph of cell drawdown vs. time.**
- **Perform radial flow correction on cell drawdown values.**
- **Create hydrograph of corrected pumping water level.**

2.1 Denver aquifer well in the northern Metro area.
2.2 Arapahoe aquifer well in the northern Metro area.
2.3 Dawson aquifer well in the southern Metro area.
2.4 Denver aquifer well in the southern Metro area.
2.5 Arapahoe aquifer well in the southern Metro area.
2.6 Denver aquifer well south of the Palmer Divide.
2.7 Arapahoe aquifer well south of the Palmer Divide.

3.0 Denver Basin Aquifer Layered Radial Flow Production Analysis.

Each analysis includes:

- **Select well location and well for analysis.**
- **Geophysical log analysis - aquifer layering**
- **Determine of the well production rate.**
- **Evaluate aquifer hydraulic conductivity.**
- **Determine annual regional drawdown.**
- **Layered radial flow model construction - input file setup.**
- **Layered radial flow model runs.**
- **Model analysis.**

3.1 Arapahoe aquifer well in the northern Metro area.
3.2 Arapahoe aquifer well in the southern Metro area.
3.3 Arapahoe aquifer well south of the Palmer Divide.

Task 4.0 - Economic Analyses

4.1 Denver aquifer well in the northern Metro area.
4.2 Arapahoe aquifer well in the northern Metro area.
4.3 Dawson aquifer well in the southern Metro area.
4.4 Denver aquifer well in the southern Metro area.
4.5 Arapahoe aquifer well in the southern Metro area.
4.6 Denver aquifer well south of the Palmer Divide.
4.7 Arapahoe aquifer well south of the Palmer Divide.

Task 5.0 - Report

5.1 Prepare Phase 2 No. 1 Report.
5.2 Discuss the DBA economic life issue.
5.3 Discuss domestic well production cost and the effects on pumping of regional water-level declines.

Table 2

Colorado Water Conservation Board and The State Engineer's Office
Senate Bill 153 - Economic Life of the Denver Basin Aquifers

HRS Water Consultants, Inc.

November 12, 1996

Phase 2 Scope of Work - No. 2

Tasks

1.0 Perform Denver Basin Aquifer Production
Each analysis includes:
- **Select well location and well for analysis.**
- **Geophysical log analysis - aquifer layering**
- **Determine of the well production rate.**
- **Evaluate of aquifer hydraulic conductivity.**
- **Determine of annual regional drawdown.**
- **Layered radial flow model construction - input file setup.**
- **Layered radial flow model runs.**
- **Model analysis.**

1.1 Dawson aquifer well in the southern Metro area.
1.2 Denver aquifer well in the northern Metro area.
1.3 Denver aquifer well in the southern Metro area.
1.4 Denver aquifer well south of the Palmer Divide.
1.5 Laramie-Fox Hills aquifer well in the southern Metro area.

Task 2.0 - Perform Economic Analysis
2.1 Dawson aquifer well in the southern Metro area.
2.2 Denver aquifer well in the northern Metro area.
2.3 Denver aquifer well in the southern Metro area.
2.4 Denver aquifer well south of the Palmer Divide.
2.5 Laramie-Fox Hills aquifer well in the southern Metro area.

3.0 Report
3.1 Prepare Phase 2 No. 2 report.
3.2 Prepare report presentation slides and materials for
Scopes of Work No. 1 and No. 2

Colorado Water Conservation Board and the Colorado State Engineers Office
Senate Bill 96-153
Economic Life of the Denver Basin Aquifer
Phase 2 Scope of Work Flow Chart
Phase 2 Scope of Work - No. 1

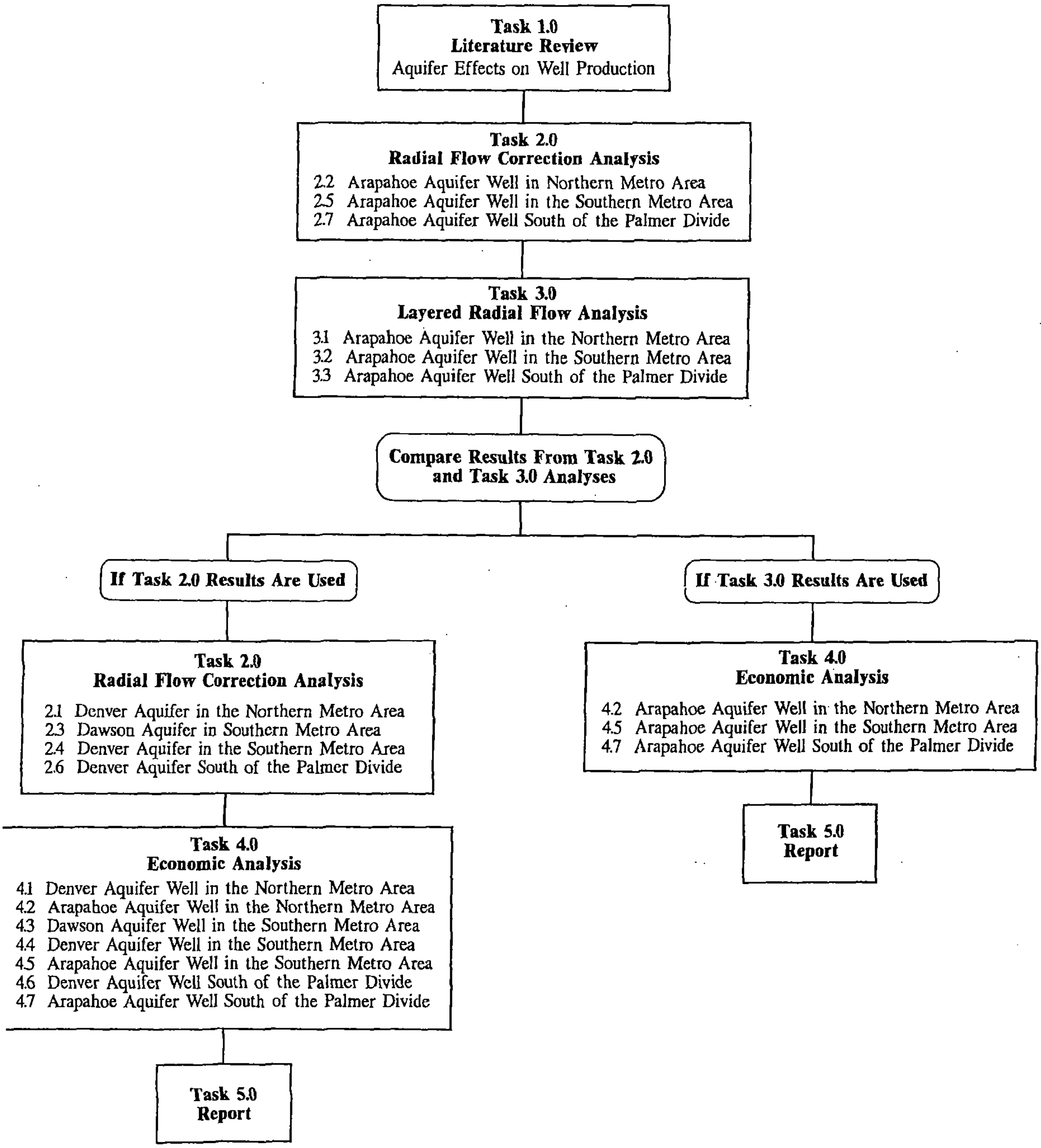

Figure 1

CWCB & SEO
S.B. 96-153 Phase 1
HRS Water Consultants, Inc. November, 1996 96018-01

MARTIN
AND
WOOD
WATER CONSULTANTS, INC.

602 Park Point Dr. Suite 275
Golden, Colorado 80401
FAX (303) 526-2624
(303) 526-2600

September 25, 1996

Mr. Will W. Burt
Deputy State Engineer
Division of Water Resources
1313 Sherman Street, Room 818
Denver, Colorado 80203

RECEIVED
SEP 27 1996
WATER RESOURCES
STATE ENGINEER
COLO.

Re: Proposal for Services
Phase I Denver Basin Study

Dear Mr. Burt:

Martin and Wood Water Consultants, Inc. is pleased to submit this proposal for hydrogeologic consulting services relating to the Phase I analyses of the Senate Bill 96-153 Denver Basin Aquifer Economic Life Assessment.

Martin and Wood has had extensive experience in ground water flow modeling throughout various hydrogeologic regions in Colorado, and in providing hydrogeologic consulting specifically in the Denver Basin. We thus have a very strong familiarity with current conditions in the Basin and have been involved with one recent study that incorporated growth projections and water usage analyses for portions of Douglas and Arapahoe Counties. The enclosed Statement of Qualifications presents a more detailed description of our qualifications and of a representative selection of some of our past projects. In addition, we have carried out numerous valuations relating to Denver Basin aquifer assets, as well as surface water assets. In this capacity we have developed an extensive in-house database of past water transactions, and in some cases, have evaluated water prices with respect to their relationship to the economic feasibility of continued resource development. We have very strong familiarity with the South Platte River system and the operation and administration of the various water rights associated with it. Finally, we have extensive programming experience that allows us to tailor model codes so that the most meaningful output formats can be generated, facilitating easier operation and understanding of results.

For the Phase I model adequacy assessment we propose the following scope of work.

A. Review the existing Senate Bill 5 model data sets for suitability to the Phase II economic assessment task.

B. Review existing available and verified model software with emphasis on proven reliability, documentation, portability, suitability to the task (especially with regard to stream-aquifer interconnection, so that the aquifer's interaction with the South Platte River can be evaluated), ease of use, and ability to incorporate some or all of the existing SB-5 model database. This would also include a preliminary assessment of the feasibility of a coupled numeric and spreadsheet or database model that could more effectively and easily allow for modeling various scenarios of economic conditions.

C. Review availability of existing well pumping data, including that available at the State and any that might be obtainable from other entities such as municipalities, Districts, etc.

D. Develop, with your office, a more concise outline of the goals of the economic feasibility study so that the choice and suitability of models can be more appropriately tailored to the task at hand.

E. Based on the above Phase II goals definition, identify the key questions to be resolved by Phase II and work with the State in developing a work plan to conduct the Phase II analyses. Inherent in this task will be development of opinions as to the level of detail and scope that will be likely for Phase II under the currently available $40,000 budget (total Phase I and II) and under extended budget scenarios that may be feasible. This would also include an estimation of the budget required to fully carry out a modeling effort that would be able to thoroughly address all of the goals identified for the Phase II portion, if it later appears that the $40,000 will not be sufficient.

We estimate that our costs to carry out the above scope of work will be approximately $8,500 to $9,500, and would propose setting that higher figure as a not-to-exceed amount. All work would be for actual time and expenses at the rates presented on the enclosed rate schedule.

Thank you for your consideration of Martin and Wood Water Consultants, Inc. We appreciate the opportunity to submit this proposal for what will be an exciting and useful project.

Sincerely,

Phillippe L. Martin, C.P.G.
Vice President

PLM:fb

SCHEDULE OF HOURLY RATES AND EXPENSES
SCHEDULE A
JANUARY 1, 1996

CLASSIFICATION	RATE PER HOUR
Principal Engineer or Hydrogeologist	$ 95.00
Project Manager	$ 75.00
Project Engineer or Project Hydrogeologist	$ 65.00
Staff Engineer/Staff Hydrogeologist	$ 55.00
Draftsperson/ Technician	$ 35.00
Typist	$ 30.00
OTHER CHARGES	
Vehicle Mileage	35 cents/mile
Outside Services And Expenses	Cost plus 10%

THE ABOVE RATES ARE EFFECTIVE FOR ONE YEAR FROM THE DATE GIVEN ABOVE.

Martin and Wood
Water Consultants, Inc.