Evaluation of Problems with Closed Basin Division Salvage Wells, Rehabilitation Method Tests, Methods for Monitoring Well Deterioration, and Recommendations for Preventive Maintenance and Rehabilitation: A Comprehensive Report

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By

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Executive Summary

Background

The Closed Basin Project of the Alamosa Field Division operates 170 wells that collect water from the Closed Basin, situated between the Sangre de Cristo and San Juan Mountains in the San Luis Valley, Colorado. This water is delivered to the Rio Grande River to partially fulfill Colorado's stream flow contribution requirements under the Rio Grande Compact. Developed starting in the early 1980s, a large number of the wells, particularly in the northern portion of the basin referred to as Stages 3, 4, and 5, experienced significant performance decline by the mid-1990s. This situation triggered an effort to improve production in individual wells, with a goal of meeting the Compact's targets in a sustainable manner.

Well problem assessment

The Closed Basin has a complex tectonic, hydrogeologic and geochemical history that contributes to poor well performance and short well life. The Stage 3-4 area in particular is known to be a discharge point, with discharge only to evapotranspiration. The limitations of wells developed in finely interbedded clays, silts and sands with thick clay units are exacerbated by very high biogeochemical activity that accelerates well clogging. Additionally, it is the conclusion of this investigation that salvage well design, construction methods, and operational decisions have all contributed to reduced performance and shortened well life.

By contrast, Stage 1-2 wells have historically performed in a steady fashion. As they are not fundamentally different lithologically, biologically, in construction or even in operation, it remains to be determined what the difference is relative to Stage 3-5 wells. Possibilities include position in the flow system and being pumped at a more sustainable rate.

The well response to excessive drawdown in Stage 3-5 (and those wells in Stage 1-2 that show decline) is a mixture of the hydrogeologic, geochemical and biological and exhibits feedback characteristics. Only a few stratigraphic units are productive at useful flow rates in any well in the basin due to Basin lithology. As wells dewater units, clays tend to collapse as plate-shaped minerals consolidate, and these do not readily re-expand when saturation conditions return. Biofouling is typically concentrated in the higher-flow zones. Thus, when they are walled off by biofilm, yield drops rapidly. The mineralogy of the clogs has been resistant to treatments selected in the past. Increased drawdown aggravates clogging by introducing more oxygen and metal-oxide deposition, and moving the damp vadose zone closer to the well intakes.

Past demonstration well rehabilitation efforts

This investigation critiqued and participated in two demonstration rehabilitation efforts in 1998 and 1999. Both demonstrated that the expectations for performance in salvage wells in Stage 3-5 are probably too optimistic. Both also demonstrated the criticality of treatment program design, including well redevelopment and chemical selection and application. The second effort, well designed to address the biological fouling problem, showed that attention to mineralogical clogging and clay behavior is also important. A proposed treatment design for maintenance was designed based on this effort.

One problem in this evaluation of the 1999 work was difficulty in performing testing before and after treatment and stages of treatment. As these were demonstration efforts, one goal was to gather information. The well use and work schedules set were not adjusted to accommodate the critical information gathering need, and equipment available, and testing done in some cases, was unsuitable for the purpose. Testing during the 1998 effort was of unknown quality. Consequently, it was almost impossible to say with certainty what the contributions of various treatments really were.

One tentative conclusion is that treatment results can seem unimpressive, but in reality, small increases in well specific capacity yield significant additional well capacity. Therefore, conducting appropriate well rehabilitation serves the mission of the Closed Basin Project.

However, more and better-controlled research is needed to make conclusive recommendations. As requested, a long-term monitoring program to assess wells rehabilitated in 1998 and 1999 is proposed, and included in an overall maintenance monitoring plan.

Sustainability and well life

Under the most ideal construction and management protocols, wells still will not last for generations in this setting. The Stage 1-2 wells experience suggest that, when operated at sustainable pumping rates, that at least a 15- to 20-year life span is possible. Such wells show signs of performance decay if pumping is increased above a certain level. Stage 3 wells in particular show that 10 years is the amortization write-off period for wells operated at higher single-wellbore flows.

Replacement schedules and budgets will depend on the level of well maintenance activity instituted as recommended by this report. More intense and effective maintenance will prolong well life. The suggestion is made in this investigation that replacement well designs should better match the realities in the Closed Basin: If a particular flow rate target is to be met, it should be made with more numerous, lower-yield well intake points, avoiding screening thick clay units, and developed properly. The wells should be operated in a sustainable manner: producing whatever yield is possible without dewatering screens, using pumps sized appropriately.

Maintenance requirements

Any kind of sustainability will require comparatively intense maintenance effort even for properly sized and designed wells due to the intensive of biological activity operating in the sediments tapped by these wells. As a rough estimate, a goal of three-year major service cycles on new sustainable or salvageable older wells should be obtainable. Older wells that have fallen below about 50 % of "realistic" original design yield (pegged at 70 % of tested original yields as a rule of thumb until better information is available) will probably be redeveloped annually.

A program of maintenance monitoring is proposed for Stages 1-2 wells to watch for trends of decline. The goal in this plan is to avoid performance decline. In this plan, selected wells are to be watched intensively, including manual testing and others monitored using the automated data collection system. Manual testing is necessary to validate automated data collection.

Maintenance for Stages 3-5 wells focuses more on a program of rehabilitative treatment and adjustment to a more sustainable pumping program, but also includes a maintenance monitoring component. The goal is to recover performance and then to achieve sustainability. Manual testing of wells treated in 1998 and 1999 and selected others is recommended to provide more detailed information than the automated testing can supply, and to validate the sometimes unreliable automated system. The maintenance treatment program defined in detail in this report is designed to address the known well performance decline agents, and is intended to be administered by a combined CBD and contractor work force.

Maintenance testing and treatment will have to be experience-based and adjusted to match real conditions. Maintenance should be made a mandatory effort through the expected working life of the project, which is presumably until whatever climatic or social change would end the need for Colorado to provide water to the Rio Grande. To do it properly will require additions of staff and equipment as recommended. Rather than being optional, the monitoring to detect changes in well performance is necessary. It is also necessary to test as recommended to avoid a continuation of well performance management by guess. The testing methods recommended are based on solid, experience-based hydrogeologic principles and are neither exotic nor difficult to perform. Once the responses of the automated system are validated during one to several years of relatively intense manual testing, the latter can be scaled back.

In the maintenance monitoring effort, one crucially important asset of the CBD is its automatic data collection and database system. Covering 170 wells manually is very difficult and time-consuming. The system provides frequent measurements over project history. However, the system itself suffers from its own maintenance needs and related inaccuracies and crucial data gaps. The importance of avoiding long periods of inaccurate or lacking flow and water level data is only now being fully appreciated. The manual testing recommended permits validation and correction of such gaps and planning for the management of the system itself.

One important component of Stages 3-5's maintenance plan is triage. Wells performing significantly below performance targets (tentatively < 30 % of an adjusted "original" specific capacity) would be abandoned. Those in low-TDS sites would be replaced. Most other wells would be placed on a rotating schedule of maintenance treatment to optimize their specific capacity. It is calculated based on information available that more water could be produced by fewer, better wells maintained and operated sustainably (and more efficiently) than is produced now as currently managed. A very specific list of recommendations is provided for discussion.

Task prioritization

The following acts are ranked in general order of importance for maintaining water output:

1. Conduct Stage 3-5 triage (using the provided spreadsheet as a simple guide to more complex actions), conduct rehabilitations needed and establish preventive maintenance actions, using the Stage 3-5 PM plan (Section 7) as a guide. Note that it is important to do the data gathering, because this is the only way to know (rather than guess or estimate) what has happened.

2. Watch Stage 1-2 wells, modify the pumping as recommended (Section 6). This attitude of watchful waiting with minimal action for now should be sufficient, but the wells should not be neglected.

3. Work on organizing the well data for ease of monitoring and visualization. Proceed as recommended in Section 8, with the existing database system, spreadsheets and ArcView, watching the specific parameters. This should be done short-term, but will permit long-term evaluation.

4. Work up the cost-benefits of recommended actions. The cost-effectiveness of implementing maintenance and rehabilitation actions to optimize water output over the long haul should be an

incentive both upstream to water users who will benefit as Colorado water can be retained in the state for consumptive use, and downstream to beneficiaries of the Closed Basin's output.

5. Stage in new construction as feasibility permits. Make the PM effort more worthwhile, permitting the elimination of unproductive wells, and installing wells that are easier to maintain.

Additionally, some practical research is needed to benefit this effort over the next few years:

(1) Answer the question of the clog: Using cone penetrometer sampling and material analyses recommended, develop preliminary physical and geochemical modeling of clogging processes.

(2) Conduct PM training and demonstration as recommended: This essentially encompasses the Section 5-7 PM monitoring and maintenance plans.

(3) Work toward "systemization" of the data analysis and gathering, using GIS, Access, and spreadsheet tools.

Proposed CBD well maintenance and rehabilitation budget

It is clear that maintenance difficulties and costs were grossly underestimated in the initial project feasibility planning and continue to be underestimated in terms of people and resources allocated to this critical task. It is recommended that these costs of O&M be reevaluated in detail. A spreadsheet table is provided that outlines a budget proposal for consideration of the costs of proposed well rehabilitation and maintenance efforts.

These are roughly prioritized by order of work, not ranks of importance.

(1) Flow and water levels from telemetry: Improve data collection and analysis reliability and eliminate gaps in reliable measurements.

(2) Equip for and conduct manual well hydrologic testing (2000-onward) in support of priority number 1 (improving flow and water level reliability) and to add information telemetry cannot supply (relative aquifer and well loss derived from step tests).

(3) Use data in modifying triage decisions. With improved and ongoing data, the CBD should revisit the spreadsheet supplied with Section 7 and update the flow rates, static and pumping UWL, Q/s values (actual and potential), and add or subtract wells as needed.

(4) Establish a protocol for biological testing and calculating a well fouling index as recommended.

(5) On the established Closed Basin base map and well locations in ArcView or equivalent, plot (a) static and long-term pumping UWL from wells, along with UWL from nonpumping monitoring points, (b) lithology and stratigraphy to provide a more systematic model of the distribution of productive and nonproductive (e.g., clay) units in the basin, (c) useful indicator water-quality parameters and calculated indices, (d) percent changes in well fouling index to provide a means of analyzing the relative importance of clogging mechanisms at various points in the basin.

(6) Develop a rational plan for salvage well rehabilitation. It is apparent that sustained, unspectacular rehabilitation efforts are a permanent part of long-term sustainability. (a) Add the

recommended crews with specific training, reporting to a professional staff person devoted to the well maintenance task, who would be responsible to the general maintenance supervisor. (b) Contract a qualified and available well service firm, especially at the beginning to get up to speed (backlog), and for a "hump period" each year. (c) Obtain specific training specific to the planned PM and rehabilitation program.

Water Costs and Benefits

In this planning process, it would be really helpful in justifying the recommended investment if the proposed costs could be balanced against quantified benefits. Such benefits can be defined in strictly economic terms, or seem to have a mixture of quantifiable and semi- or nonquantifiable characteristics. While strict cost-benefit balances are valuable, U.S. Bureau of Reclamation, in addressing the economic analysis of maintenance, recommends that such analysis include factors beyond mere economic return. In the case of the Closed Basin project, such a benefit would be reliable water output to meet Compact requirements. These requirements do not have an economic component.

However, benefits can be quantified in economic terms if dollar values can be placed on benefits using available methods in water economic value. As a justification for the costs identified, it is recommended that

(1) A monetary value should be placed on the water pumped into the Rio Grande, using some value such as dollars per acre-feet of water available to upstream Colorado irrigators or potential downstream customers. The USBR uses similar environmental economic estimations of benefits in evaluating other projects.

(2) Costs of pumping water be charted. In this case, benefit (B) is a reduction in the cost of operation via the efficiency improvements gained through maintenance. As with the objective water data recorded in the system, these data can be recorded and updated, and calculations made using available spreadsheet software and formulas.

With the existing body of knowledge and the recommended maintenance, operational, testing and further information gathering, a rational system of sustainable operation can be built that will support this project through its institutional life.

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In fulfillment of URS Greiner Woodward Clyde Federal Services subcontract DEN23605, Closed Basin Salvage Well Maintenance and Rehabilitation Planning, Smith-Comeskey Ground Water Science has, over 1999, produced a series of reports on research and recommendations task elements for the U.S. Department of Interior Bureau of Reclamation Technical Services Center (TSC). This report, fulfilling project task 13, is a final compilation of these reports into a coherent whole. The various sections of this report incorporate information and review comments collected since initial project submittal. Readers of the task-element reports will note some revision of and addition to conclusions and recommendations based on information and experience gained since initial submittal.

The organization of the report is intended to provide the reader with a background on causes and influences on salvage well performance decline, a background on and results of two specific experiments in well rehabilitation, a discussion of monitoring methods useful in well performance maintenance and commentary on Alamosa Field Office monitoring capability, and recommendations for a salvage well preventive maintenance program and related future work.

Salvage well performance is vitally important to the mission of the Closed Basin Division, which is to supply ground water for transfer to the Rio Grande under the treaty requirements of the Rio Grande Compact. The intent of the work is to provide a framework for a comprehensive salvage well maintenance plan so that wells in the Closed Basin project area can supply the necessary amounts of water in a cost-effective manner as long as this water is needed to maintain Rio Grande channel flows.

This report is respectfully submitted to the TSC under the above-referenced subcontract by Smith-Comeskey Ground Water Science on behalf of the contracting firm, and was prepared by the undersigned. It is to the best of his knowledge and belief a valid and complete review with recommendations for the purpose intended, and fulfilling the SOW task element 13 of D.O. 116 under the referenced URS Greiner Woodward Clyde Federal Services (WCFS) contract.

The advice, input, research and project assistance and support of various people associated with the TSC and Alamosa Field Office, input from project contractors and past researchers, and the contract management services of WCFS are gratefully acknowledged. The collaborative nature of this work made it much more valuable.
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Executive Summary

To be supplied

1. Review of Hydrogeochemical, Hydrological, Construction and Operational Effects on the Deterioration of Closed Basin Salvage Wells

Introduction

Deterioration of Closed Basin salvage wells apparently has multiple contributing factors. An obvious potential cause that has been studied extensively, including the work summarized and expanded by Hernandez (1998), is biological fouling. Biofouling occurrence is apparently intense, particularly in Stage 3-4 wells, based on analytical results. However, numerous other factors influence the intensity of biological growth, biofilm development, and the effects on the hydraulic performance of wells.

This chapter is presented as a summary for use in understanding the causes and scope of the problems with the Closed Basin salvage wells and how to address these problems to aid in the goal of providing long-term maintenance of water production for the Rio Grande Compact. These factors are summarized in turn in this section to provide a:

(1) Convenient background history of the current state of knowledge of causes for reference and

(2) Conceptual model of deteriorating conditions for ongoing well rehabilitation and maintenance planning.

Closed Basin Depositional History and Hydrogeology

Tectonic, depositional, and subsequent hydrogeological history typically have a profound influence on the operation of wells in a hydrogeologic setting. This “background” influence is subsequently modified by biological, construction and operational mechanisms.

Tectonic

Tectonic activity sets the framework for regional hydrology in any location, and this is particularly the case with the San Luis Valley. The valley and its included Closed Basin are situated between the San Juan Mountains on the west and the Sangre de Cristo Mountain range in the east, in a graben on the downthrust side of the Sangre de Cristo fault (Rio Grande rift zone). Orographic precipitation is an obvious effect of these geographic features, with snowmelt runoff contributing virtually all the water used in irrigation and recharging the aquifers of the valley (Emery et al., 1973). In the Closed Basin, recharge is through mountain front and stream infiltration.

The Sangre de Cristo Mountains are comprised of a series of horsts formed on the upthrust side. The San Juans are underlain by Tertiary volcanic rocks (Huntley, 1979b), which extend from the mountains into the valley. These include the Conejos Fm. and overlying tuffs (identified in shallow wells in the northern San Luis Valley) that interbed and inter-finger with alluvial sedimentary materials (Huntley, 1979a). Volcanic cones to the south of the Closed Basin area bear witness to the extensive volcanic activity in the area, generating significant tuff and ashfall parent material for later sedimentary action to distribute.

Faulting that has continued into the Holocene (but apparently has subsided) provides the framework form the valley’s overall hydrology. One resultant feature of this activity is, of course, the isolation and unique character of the Closed Basin. Uplift in the southeastern portion of the basin resulted in a lack of natural flow outlets for surface water drainage in the valley. The Closed Basin became the "sump" where fine sediments collect (essentially Stage 3).

Sedimentary deposition

The geology and stratigraphy of water resources in the San Luis Valley was comprehensively described as early as Siebenthal (1904). In the sedimentary section, prevailing northwesterly winds have transported sand and silt from exposed lake beds across the valley in relatively recent times. These are visible as the great mass of sand dunes at the west foot of Mosca and Medano passes of the Sangre de Cristo Mountains comprising the Great Sand Dunes National Monument. Alluvial deposits formed as the valley is the discharge route for flow from both the San Juans and Sangre de Cristo highlands. Features include alluvial fans, various low-energy stream deposits and lacustrine deposits. These are all relatively recent in age.

Paleocene and newer units of various descriptions are interbedded, with Pliocene-Pleistocene age interbedded sands and clays (Alamosa Fm.) dividing the confined and overlying Quaternary-age unconfined aquifers (Huntley, 1979b).

In the Closed Basin itself, sedimentary deposits described are characteristic of low-energy deposition (interbedded clays, sands and silts) with occasional thin zones of sandy gravel (AFO-supplied boring logs and data records of Hernandez, 1998). Small lakes and evaporation pans such as described by Hernandez (1998), using information from earlier reports, exist at the present, and apparently have been a feature throughout the basin's development. These fluvial-lacustrine deposits exhibit closely spaced facies changes and also vary over short distances horizontally (Mayo and Webber, 1991). This shifting low-energy, slow-flow, impounded setting has probably been characteristic of the Basin's entire Holocene-Recent history.

Hydrogeology

These sedimentary features result in a relatively low-yielding hydrogeology, compared to the highly productive northern and western valley, such that "virtually all attempts to develop irrigation wells in the Closed Basin have failed because of the inability of the shallow valley-fill to yield water readily" (Hernandez, 1998).

Additionally, the Closed Basin project occupies the central portion of the San Luis Valley, which functions as the terminus of the ground water system. The "sump" area identified in many of the publications is the topographic low in the valley and functions as the discharge area for the flow system. It is here that the zone of saturation is near the surface and water leaves the flow.
It has been recognized since the early 1900s that the unconfined aquifer zone in the San Luis Valley Closed Basin area had discharge only to evapotranspiration. Huntley (1979b) notes that virtually all discharge from the valley is evapotranspiration.

The hydrogeological features and ground water flow system of the Closed Basin unconfined aquifer have been relatively well described. Water enters the system at the perimeter of the valley where surface stream flow infiltrates into the alluvium within a few miles of entering the valley (Leonard & Watts, 1989). Water moves both (1) horizontally through the alluvium, or (2) due to head relationships, downward into the confined units below. Also in the sump area, head relationships are such that water moves from the leaky confined aquifer to the unconfined aquifer to then be discharged. Emery et al. (1973) Plate 3 illustrates that the lowest transmissivity (hydraulic conductivity x unit thickness) areas are found in the Closed Basin. Mayo and Webber (1991) also provided a discussion of the hydrogeologic framework and examined ground water movement in Stage 3 and its influence on pumped water quality.

Hydrogeochemical Influences

These hydrologic features (recognized and accounted for in the planning for the Closed Basin Project) conclude a scenario that provides for a very active ground water hydrochemistry:

- Complex and recent tectonic activity, including deposition of chemically complex and somewhat soluble tuffs with cation-exchange capacity, pyroclastics, and intrusives, weathering to clays, silts and sands with complex mineral contents, including redox-sensitive metals such as iron, manganese, copper and arsenic (found in salvage well water).
- The short geologic history, relative aridity since the end of the Pleistocene, and lack of outflow results in a system that has experienced little hydrologic flushing. Quality is better along the margins of the unconfined aquifer system and worst at its center. What has been deposited in place (including all significant nutrients, organic carbon, and electron acceptors for biological activity) has remained, and in fact is somewhat concentrated in the discharge zone.
- Upward flow from the confined aquifer through the dividing clay units (which may be controlled by faults) adds another layer of chemical complexity.

The results are seen in various summaries of water conditions in the San Luis Valley. For example, Emery et al. (1973) shows areas of very high salinity hazard and nitrate concentrations centered in the Closed Basin. Causes are in dispute. While earlier authors attribute mineral concentrations to ET in the sump region, Mayo and Webber (1991) describe isotopic analyses that show that ground water is affected by "excessive" surface evaporation (relative to the mean meteoric water line) prior to recharge.

Biological Contribution to Aquifer and Near-Well Hydrogeochemistry

Biology is a contributing and complicating factor, both in prevailing Closed Basin hydrogeochemistry and its modification around pumping wells. From file reports, there is a significant biological presence in the basin shallow aquifer:

- Significant deposition of organic matter occurs in valley fill around old lake and stream depositions, including the “channel” deposits discussed by Hernandez (1998).
- Hernandez also notes Siebenthal’s report of animal and plant debris recovered from wells “all over the basin” (mostly in the artesian formations) -- indications of vast amounts of virtually unweathered organic matter that can support biological activity in the aquifer.
- Reports of methane in deeper wells, centered in the Closed Basin area, and the Mayo and Webber (1991) tests discussion, are evidence of significant anaerobic microbial activity (reduction from CO_2/HCO_3^- to CH_4). Methane isotopic composition reflects recent biological methanogenesis.
- High total dissolved solids (TDS) is itself an indication of microbial activity. Various microbial mechanisms result in weathering from formation material and adding solutes to water.
- Mayo and Webber (1991) point out that the solute compositions of the TDS also reflect a combination of methanogenesis effects and cation exchange that results in a relative overabundance of Na^+ in the high-TDS waters.
- As there is upward flow from the deeper zones, activity and carbon in the confined system are likely to be available to the unconfined system (even if it did not have its own organic carbon reserves).

- Hernandez (1998) echoes Mayo and Webber's (1991) linkage between the location of the most troublesome Stage 3 wells and the lake area (with presumably abundant carbon resources plus methanogenesis release of excess C). These are further indications of the relationship between the hydrogeologic setting and biological activity (both macro- and microscopic).

Hernandez (1998) ably summarized past investigations into the microbial influences on clogging in the wells. These do not have to be dissected further except to note that:

- "Iron bacteria" were described from the beginnings of analyses in 1994, with variety in type noted. Identification of these microflora by microscopy is inconclusive and dependent on the analyst's interpretation. However, as reported, *Crenothrix polyspora* is characteristic of organic-rich alluvial formation wells and is credited with being a methane-oxidizer. *Sphaerotilus natans* is also characteristic of more organically rich settings (including activated sludge). *Gallionella* and *Leptothrix* spp. reported are typical of mature water well biofilms. The methodology used by Sangre de Cristo Laboratories (SDC Labs) in culturing these and other biofouling microflora is based on *Standard Methods for the Examination of Water and Wastewater* (APHA-AWWA-WEF).
- The Water Systems Engineering (WSE) reports from 1994 to 1996 reveal an evolving methodology that is technically very interesting. While ultimately not useful in quantifying the biofouling situation (correlation between ATP and plate count results and biomass or activity is not convincing), the results reveal that a diverse microflora is present. These microflora are consistent with what could be expected in an aerobic, organically rich, recent alluvial setting. While there is a tendency to focus on "iron bacteria" in well performance problem analysis, the actinomycetes reported by WSE (and also SDC Labs) are not to be overlooked as efficient clogging agents in sediments. They also typically require significant organic carbon.
- The presence of identified microflora in some reports and not others (for example, sulfate-reducing bacteria found by SDC Labs (1998 report) and their consistent absence in WSE reports) reflects both differences in methods and diversity in the ground.

The November 1998 WSE report is certainly disturbing as we plan future maintenance. Microscopic analysis from SW-86 reported rotifers, protozoans, "green particles" and "large fiber growths." SW-84 results added nematodes. These samples (apparently grab samples) were taken in well outflow at the well structure (and not at the canal, for example), based on the Laguna Construction Co. well cleaning test report (1999).

Rotifers and nematodes are relatively large, complex organisms often found in near-stream hyporheic zones, but not often encountered in wells. Both are active predators and typically act as tertiary consumers in microbial food webs. If we assume that their presence is not an artifact of backflow from the canal (which is, however, a possibility), they are another indication of a rich microbial ecology in the near-well environment. If collected in visible quantities in a transient grab sample, instead of on filters, their numbers are high in situ. The distribution of these organisms, and the contribution of filamentous microflora other than "iron bacteria" are factors that should be explored further.

Another factor that should be confirmed further is the actual nature of so-called "iron bacteria" and their geochemical relations in the Basin wells. *Leptothrix* spp. have been described by WSE. These can be manganese-depositing organisms and SDC Labs (6/24/1998 and 12/29/1998) reports the presence of "manganese producing bacteria" at a "density" about equivalent to "iron producing bacteria." As Mn is prominent in the AFO-produced water chemistry data, this is not unexpected. MnIV-oxide mineral are significantly less soluble than the typical microbially deposited FeIII mineral, ferrihydrite. Such a solubility difference could be a factor in the weak results from well cleaning to date for at least some wells.

Effects of Hydrologic Events on Hydrogeochemistry

A final interesting phenomenon that may be relevant to the relationship between hydrology, the timing of the project, and microbiology is the possible effect of a pulse of recharge in the late 1980s on ground water chemistry in Closed Basin wells. Attached is a “change in unconfined aquifer storage” chart from the Rio Grande Water Conservation District and three data trend charts generated from AFO water quality data. TDS dips occur centered on 1991 in two of four wells charted (the ones with normally higher TDS), which would be consistent with a pulse of recharge reaching wells after several years of travel time. SW75 (one of the “pulsing” wells) also shows similar drops and recoveries in conservative ions (Na^+, Ca^{2+}, SO_4^{2-}, and HCO_3^-). Such presumably oxygen-rich recharge could have fostered an intensification of biological activity just as the Stage 3-4 wells were being constructed and brought on line.

In 1990 and 1991, pumping tests were conducted on SW-67 to evaluate vertical flow effects of pumping (Mayo and Webber, 1991). A feature of this test was its evaluation of the differential responses of four hydrostratigraphic units encountered by the well screen.

In the resting state at SW-67, there is a natural upward vertical flow from Unit 4 (confined) toward unconfined units 1 to 3. According to the analysis of Mayo and Webber (1991), water level actually rose in Unit 4 (not screened in SW-67) during the test, while water levels dropped over time in Unit 1 (also not in direct connection with the screen) and screened Units 2 and 3 (as would be expected). The rise in Unit 4 could have been due to reduced pressure in the unconfined units, but is also attributed to exsolving methane gas. Vertical leakage from Unit 1 around wells through the gravel pack is inferred based on reduced hydraulic head in Unit 2 during pumping. Thus, although in the natural state, inter-unit mixing is not highly likely, units with very different water qualities can be mixed at wells. This is reflected in widely varying water quality (e.g., TDS) over time for individual wells (Mayo and Webber, 1991). The same authors describe Stage 3 spatial variability in water quality as highly variable.

Current Salvage Well Design and Construction

Information we have been supplied on details of construction and development pertains to Stage 3-4-5 wells, which exhibit the most problems. Project well histories were supplied by the AFO for SW-84, SW-91, SW-99, and SW-103. These histories include hard copy narratives of the construction practices used, specifications, well test data (hydrologic and water quality), and as-built dimensions and equipment. Well construction history is summarized as follows:

Well	Comments
SW-84	1983 construction. Pump installed 1986. Good initial pumping data. Note on 3/12/1986 test (805 - 857 gpm): However, it was run under vacuum. “When plug was removed, allowing air in, well began cascading and output dropped way off.”
SW-91	1983 construction. Pump installed 1986. Good step test data (1983 & 1986) for use in comparison over time. “Black organic material” encountered at 10-18 ft (SWL = 1 ft, dewatering needed during pit construction).
SW-99	1983 construction. Pump installed 1986. Good initial pumping data.
SW-103	1985 construction. Pump installed 1985? Good initial pumping data.

Construction features pertaining to performance decline

Materials encountered: Boring sample logs and gamma and resistivity geophysical logs confirm the mixed sedimentary materials, with higher resistivity units higher in the intervals. "Black organic material" was noted in a thick unit in SW-91 which is likely to be rich in organic carbon deposits.

Drilling fluid: The wells constructed in 1983-1985 were drilled using direct mud rotary methods, with a surface casing hole drilled and casing grouted in, then the conductor casing and screen with filter pack installed inside a temporary casing, which was withdrawn to expose the screen and filter pack. Development was by jetting, followed by initial test pumping. Revert (Johnson Division, wells SW-84, -91, -99) and Variflo (unknown product, SW-103) are described as the drilling fluid additives. Revert is a natural polysaccharide guar gum polymer that "forms a low-solids, biodegradable polymeric drilling fluid that does not introduce non-native clay particles into water-bearing strata" (Driscoll, 1986). Variflo is presumably a similar product from another supplier.

Revert viscosity (a function of polymer integrity) breaks down in a matter of days at ambient ground water temperatures (Driscoll, 1986). The polymer product's excellent viscosity vs. fluid weight characteristics and the desire to minimize clay addition in such a clay-rich environment was probably a deciding factor in the choice of this system for the specifications. According to the procedure description for Revert, the contractors mixed and used the product correctly according to practice at the time.

A key feature in this discussion is the matter of being biodegradable. It is now well demonstrated that the Closed Basin sediments support a significant and diverse microbial population, including active filamentous heterotrophs such as actinomycetes and *Pseudomonas* spp., capable of polysaccharide hydration. Despite breakdown due to shock chlorination after the wells were drilled and subsequent development, it is likely that using these products, which are sources of polysaccharides, provided some additional assimilable organic carbon (in the form of monosaccharides) in the formation to "jump start" a biofilm bloom in the newly aerobic borehole environment.

Like desert plants, microbial populations in aquifers typically are adapted to rapidly take advantage of such "windfalls" of fuel, nutrients, electron acceptors and moisture. In fact, in breaking down the polymer structure, chlorination probably made the carbon more available to some bacteria. This was likely a transient situation, after which biofilm development was sustaining with other available carbon and recycling within the biofilm.

Development: Jetting at 200 psi (as recorded for SW-91) was employed as the development method. Jetting duration was recorded as being about 3 to 7 hr (stopped at 7 hr on SW-91 by USBR inspector), with pumping development following. This was probably somewhat short and likely did not remove all damage. Clays could have been smeared and dispersed across sandy units. In SW-91, it is noted that no gravel pack had to be added. This probably indicates that insufficient particle motion was induced during jetting, as some finer fractions of filter packs should come out of the screen during development (Driscoll, 1986).

Some likely changes to suggest

- No organic, biodegradable polymers should be used in the future. In general, these are out of favor in the industry for the reasons stated above.

- Use bentonite direct mud rotary through the test and construction drilling phases and be very strict about methods requirements, up to and including requirement of "mud school" attendance and proper mud testing equipment. Alternatively: Use of cable tool methods in these shallow, easily drilled sediments is very practical and results in a clean completion without significant use of drilling fluid additives.
- Use of an enclosed mud tank system for fluid circulation on mud rotary drilling projects. No dug pits should be used.
- Development should be rather lengthy (time developed on first of the new-phase wells) and performed to a standard such as sediment removal.
- As per comments on proposed new well specifications, the design should be considered in light of performance history.

Please review the discussion of the proposed new well design later in the report. Comparisons to Stage 1-2 construction features is probably useful. However, changes in construction and development practices that can now be made with hindsight in the Stage 3-4-5 phase should be applicable to planned new construction throughout the project area.

Operational History

The first salvage wells were construction in the early 1980s (stage 1-2) and construction continued through the 1990s (stage 5). Reduction in yield from some project wells was noticed in 1993-1994, which led to efforts to determine causes and to rehabilitate wells. A major work in this effort was the report by Hernandez (1998), which summarized work prior to that time, and added statistical analysis of problems.

Effects of intermittent use

It is common wisdom (but poorly supported experimentally) in the ground water industry that wells exhibit the least decline in performance over time if used continuously or in rotation. This is the case now in operations. However, as discussed, the Closed Basin system can be shut down in years of extraordinarily high or low flow in the Rio Grande basin. This is reported to have been the case in the mid-1990s, when Stage 3-4-5 wells show long periods of inactivity in flow records supplied by the AFO. Stage 1-2 wells were reportedly used more consistently during this period.

Flow record examples supplied by the AFO in March 1999 show trends toward decline in capacity from year to year, comparing pre-1992 to 1997-and-later data. Wells were used intermittently in the intervening years. In 1991 and before, wells charted were pumped at significantly higher rates, but more inconsistently, than 1997 and later.

These data do not confirm harm in Stage 3-4-5 wells from the hiatus, but they also suggest that the long "rest" periods did not help the wells. More consistent use of Stage 1-2 wells did not harm them, as their histories also show a pattern of more consistent performance. Several of the Stage 3-4-5 charts more easily support the next topic, excessive drawdown.

Effects of excessive drawdown

An identified component of sustainability in a variety of hydrogeologic settings is the concept of safe yield. This concept has traditionally been discussed in the context of water resource management, but it also is a factor in sustaining well operations. Irrigation has been discussed as being not economical to sustain in the Closed Basin (Hernandez, 1998), basically due to low per-well yields.

It is our opinion that one factor in the relative success of the Stage 1-2 wells is that they have not been pumped at an unsustainable rate. Judging from both the Hernandez and AFO data charts provided, the large majority of these wells have maintained a steady pumping rate despite being operated much as the Stage 3-5 wells are (pumping level consistently in the screen). It appears that these wells are operating within a pumping margin of safety in which potentially clogging mechanisms have not yet affected production greatly.

Several wells in Stage 1-2 that have been bumped up in production (e.g., SW002 to SW004, SW008-SW010, SW013, SW019 and others) show characteristic decline curves after the increase in pumping rate occurred, whereas they were steady in yield before. This effect may be a function of age that may have occurred anyway, but was made apparent more quickly by the increase in pumping.

Stage 3-4-5 well pumping data reported and charted by AFO suggest that developed design capacities and pumpage prior to 1997 were unsustainable. Flow patterns for the well examples discussed in March 1999 show higher yields, but more erratic performance in 1991 and before. Earlier charts analyzed by Hernandez (1998) and Jack Cunningham (supplied in 1998) show steep decline curves in wells in these stages, typical of wells that are pumped at unsustainable rates.

The well response to excessive drawdown is a mixture of the hydrogeologic, geochemical and biological:

- Only a few stratigraphic units are productive at useful flow rates in any well in the basin due to Basin lithology and these are more likely to be in shallower intervals, based on a review of borehole and geophysical logs.
- As wells dewater units, clays tend to collapse as plate-shaped minerals consolidate, and these do not readily re-expand when saturation conditions return.
- Biofouling from actinomycetes, slime-formers and metal-precipitating bacteria is typically concentrated in the higher-flow zones. Thus, when they are walled off by biofilm, yield drops rapidly.
- MnIV-oxides are poorly soluble, even compared to FeIII oxides, and thus resistant to removal in well cleaning.
- Increased drawdown aggravates clogging by introducing more oxygen and metal-oxide deposition, and moving the damp vadose zone (a home for actinomycetes) closer to the well intakes.
- Induced downward flow from higher-TDS units along the gravel pack during pumping also likely results in deposition of carbonates and sulfates in the filter pack (see the BCHT test chapter).

Expectations in Well Maintenance and Life Span

As past and present AFO management is acutely aware, the Closed Basin is not an optimal environment for long well life or high performance. This introduction summarizes a long and interactive set of circumstances that have resulted in the current state of having a high fraction of the total well population operating at a fraction of design capacity.

Realistic expectations

Under the most ideal construction and management protocols, wells still will not last for generations in this setting. The Stage 1-2 wells experience suggest that, when operated at sustainable pumping rates, that at least a 15- to 20-year life span is possible. Such wells show signs of performance decay if pumping is increased above a certain level. Stage 3 wells in particular show that 10 years is the amortization write-off period for wells operated at higher single-wellbore flows.

The Project should probably budget and schedule for:

(1) 10-year replacement intervals if it is likely that maintenance will be sporadic and the higher flow rates (as indicated in the 1998 plans for replacement SW-74) will be expected from the new wells planned.
(2) 15- to-20-year replacement on the above if maintenance can be sustained as planned. If greater life span is achieved, it is a bonus and an incentive to sustain maintenance.
(3) Longer life if a more sustainable per-well yield can be planned. Yield from these wells will also be more predictable.

Maintenance

Subsequent chapters detail maintenance planning. Any kind of sustainability will require comparatively intense maintenance effort even for properly sized and designed wells due to the intensive of biological activity operating in the sediments tapped by these wells. As a rough estimate, a goal of three-year major service cycles on new sustainable or salvageable older wells should be obtainable. Older wells that have fallen below about 50 % of "realistic" original design yield (pegged at 70 % of tested original yields as a rule of thumb until better information is available) will probably be redeveloped annually.

Maintenance testing and treatment will have to be experience-based and adjusted to match real conditions. Maintenance should be made a mandatory effort through the expected working life of the project, which is presumably until whatever climatic or social change would end the need for Colorado to provide water to the Rio Grande.

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Also files kindly supplied by Ella Mae Herrara and the AFO staff. Their work on accessing, organizing, interpreting and charting this vast and complex data set is gratefully acknowledged.

Attached figures

2. A Review of Past Well Cleaning Efforts: Salvage Well Remediation Tests at Closed Basin Division, San Luis Valley Project, by Laguna Construction Company

Purpose

Numerous attempts have been made to rehabilitate salvage wells that have exhibited unacceptably reduced levels of performance. Due to the scale of the well declines and the project and treaty implications, a search for optimal methods for well rehabilitation began very early on in the project's history. A selection of the methods known to the industry over time have been proposed and tried, including a parade of innovative chemical and physical development treatments. This section and the next describe two tests of methods conducted during this project period. Another such test of a method is planned for Spring 2000.

This well rehabilitation review effort was conducted using (1) information that was current in early 1998 and (2) using a scope of work incorporating that body of information and an informed review of modern well-cleaning methods. The purpose of this review is to evaluate the methods and results of these well cleaning attempts to provide lessons for future rehabilitation and maintenance actions and overall well operation and maintenance strategy in the Closed Basin.

The basis for this review is (1) the report copy entitled "Final Report" dated March 1, 1999 and provided by the Alamosa Field Office (AFO) and (2) additional communication forwarded by the Bureau of Reclamation (USBR) Technical Services Center (copies attached). The well rehabilitation work conducted was performed under Contract # 98CS 8100 26.

Scope of Work and Work Completed

The original "Statement of Work, Salvage Well Remediation Tests, Closed Basin Division, San Luis Valley Project, Colorado" (SOW) was reviewed by Smith-Comeskey under the 1998 informal work agreement with the USBR Technical Services Center (TSC). This SOW called for cleaning 10 wells that were selected by the AFO-TSC-consultant team. This number was subsequently reduced to five (SW-79, -82, -91, -100 and -150) due to a combination of logistical and weather problems.

Well Deterioration Causes and Impacts on Treatment Effectiveness

A review of probable causes of salvage well performance deterioration was part of informal consultation with the Closed Basin Division (CBD) and TSC in 1998 and the current work, and summarized in Section 1. Among the influences on the 1998 treatment results:

(1) Biofouling is a major factor identified in well clogging.

(2) Biofouling occurrence and impacts were aggravated by:

- Modest aquifer hydraulic conductivities such that biofouling, combined with fine sediment presence, can cause clogging.
- Significant non-productive clay unit intervals. Additionally, clay may have been smeared during construction and not adequately developed out.
- The design of existing wells. Screen and filter pack slot sizes and screen lengths are remarkably uniform, and span significant clay intervals.
- Operational patterns, especially in the early 1990s.
- Current operation with pumps 25 to 30 ft below the top of screens, a condition associated with rapid filter pack and screen clogging.

A Review of Procedures

The following is limited to procedures that affected the final outcome, well hydraulic impacts of the treatments and how they were evaluated (Laguna report Section 3.0 and on). These treatments were conducted per the August 1998 SOW with some field modifications.

Specific capacity pumping tests

For pre-treatment benchmarking, these were conducted at a single constant rate for three hours. The rate was selected to be approximately 20 to 40 per cent of the original design capacity of the wells as provided by USBR from AFO records. The USBR site inspector directed an increase in rate in some tests. The basis for picking these flow rates is not provided, but was probably from an on site evaluation of realistic expectations.

It is common practice in evaluating impaired wells with a relatively unknown performance history to conduct multi-rate step tests (Helweg et al., 1983). Using available analytical procedures (Helweg et al., 1983; Driscoll, 1986; Kruseman and de Ridder, 1994) good assessments of both (1) specific capacity at various rates and (2) relative well and aquifer components of the total well loss can be made. Such tests would have made the before and after evaluations somewhat less tenuous, and permit comparison to original specific capacity values. As they were run, specific capacity values (Table 3.1) are good values for the specific flow rates at which they were tested, and show incremental changes due to treatments.

Mechanical cleaning

Due to doubts expressed by TSC personnel about documentation of mechanical cleaning in the Laguna report body, and questions about effectiveness, the following tables were made as summaries of Laguna report's included field logs.

Mechanical cleaning log of SW-79

Date	Type	minutes	Date	Q/s (gpm/ft)
10/20/1998	jetting	91	10/10/1998	6.74
10/24/1998	surging	39		
10/25/1999	surging	52		
10/28/1998	surging	91	11/09/1998	9.91
11/10/1998	surging	105		
11/15/1998	surging	105	11/24/1998	9.75
12/14/1998	surging	276	12/17/1998	9.98
Total		12.65 hr (+ test pumping)		

Some observations on SW-79:

(1) The surging (conducted 39 to 276 min. per day spread over almost eight weeks) was never sustained for the hours at a time necessary to develop a harmonic action in sand grains, and when restarted after an interval, energy had to be expended to start the motion again, rather than moving out fines and debris.

(2) The relatively limited time developing (ranging from 11 to about 23 hr per well) was probably insufficient.

(3) However, the effectiveness of much of the development action was comparable to other efforts and may be considered as good as can be expected (see the next section). Whether these results are considered acceptable or not would depend upon the standards employed.

Mechanical cleaning log of SW-82

Date	Type	minutes	Date	Q/s (gpm/ft)
10/17/1998	jetting	77	10/09/1998	3.57
10/19/1998	surging	91		
10/23/1999	surging	91		
10/24/1998	surging	60	11/15/1998	3.65
11/16/1998	surging	105		
11/30/1998	surging	122	12/05/1998	4.61
12/06/1998	surging	224	12/09/1998	4.52
12/10/1998	jetting	150		
12/11/1998	jetting	450	12/11/1998	4.85
Total		22.83 hr (+ test pumping)		

Mechanical cleaning log of SW-91

Date	Type	minutes	Date	Q/s (gpm/ft)
10/21/1998	jetting	84	10/18/1998	4.44
10/25/1998	surging	88		
10/31/1999	surging	126		
11/09/1998	surging	30	11/09/1998	4.95
11/10/1998	surging	112		
11/16/1998	surging	119	11/19/1998	3.88
12/01/1998	surging	105	12/06/1998	4.19
Total		11.1 hr (+ test pumping)	12/19/1998	5.51

SW-82 and -91 results are marginal at best. Reasons probably depend upon local conditions at these well sites.

Mechanical cleaning log of SW-100

Date	Type	minutes	Date	Q/s (gpm/ft)
10/15/1998	jetting	86	10/09/1998	4.78
10/17/1998	surging	91		
10/22/1999	surging	30		
11/06/1998	surging	98		
11/07/1998	surging	265	11/13/1998	5.36
11/14/1998	surging	105		
11/17/1998	surging	91	11/21/1998	5.5
12/01/1998	surging	122		
12/06/1998	surging	240	12/11/1998	7.66
Total		18.8 hr (+ test pumping)		

Mechanical cleaning log of SW-150

Date	Type	minutes	Date	Q/s (gpm/ft)
10/12/1998	jetting	66	10/08/1998	7.27
10/14/1998	surging	30		
10/16/1999	surging	135		
10/17/1998	surging	15		
10/19/1998	surging	20		

10/20/1998	surging	46	10/22/1998	13.7
10/23/1998	surging	98		
10/28/1998	surging	126	11/11/1998	6.46
11/16/1998	surging	98		
11/18/1998	surging	105	11/22/1998	7.47
12/13/1998	surging	126	12/16/1998	8.76
Total		14.4 hr (+ test pumping)		

SW-100 likewise shows results comparable to subsequent methods (next section) while SW-150 is little improved despite similar development times.

Chemical treatments

It was apparent that of the various chemical choices made, none had a dramatic impact that stood out from the rest, although improvements occurred. The initial treatments of chlorine then glycolic acid + sulfamic acid + QC21 additive appeared to have the most impact:

Well	Date	Initial acid treatment	Improvement in Q/s	Final Q/s	Q/s +
SW-79	10/28/1998	glycolic+sulfamic+QC21	6.74 - 9.91 gpm/ft	9.98	3.24 gpm/ft
SW-82	10/23/1998	glycolic+sulfamic+QC21	3.57 - 3.65 gpm/ft	4.85	1.28 gpm/ft
SW-91	10/25/1998	glycolic+sulfamic+QC21	4.44 - 4.95 gpm/ft	5.51	1.07 gpm/ft
SW-100	10/221998	glycolic+sulfamic+QC21	4.78 - 5.36 gpm/ft	7.66	2.88 gpm/ft
SW-150	10/18/1998	glycolic+sulfamic+QC21	7.27 - 13.7 gpm/ft	8.76	1.49 gpm/ft

As with redevelopment time, SW-100 appeared to gain the most from repeating dosage. The change to hydrochloric acid possibly had a beneficial effect in this well (possibly due to its effect on deposited carbonates), but development may also have been the cause (as was the case with SW-79). SW-150 actually declined significantly in specific capacity after the first round of treatment, then rebounded slightly.

The lengthy acid contact times, adding acid to keep pH < 2 appeared to have no benefit. The chlorine treatments added after the initial treatments also were apparently ineffective. Chlorine demand was substantial, which was as expected. Chemical dosage concentrations were adequate to generous. The order of chlorination and acid treatment doses apparently was not significant. Calcium hypochlorite treatment may have resulted in solids deposition in the well (Ca^{2+} + supersaturated HCO_3). Experimentation would be needed to determine whether this was likely to occur in these wells.

Revisions in Procedures Recommended by Contractor

Laguna's well treatment contractor, Layne-Western Co., and their advisors made worthwhile recommendations to make improvements, and provided valuable information to move ahead in planning future activities (Laguna report Section 6.0 and other communication).

As demonstrated above, the chemical changes recommended and made were not necessarily an improvement, but may have been more cost-effective, given the cost of glycolic or acetic acid as delivered to Alamosa. The notation that jetting was the preferred mechanical treatment is a recommendation that may be considered, but it has potential drawbacks.

Performance Evaluation

Based on review of the report

As indicated in Table 5.3 of the Laguna report, modest increases were made in specific capacity, and SW-79 and SW-150 were improved to 70 % of reported original specific capacity. However, SW-150 was at one point above its reported original specific capacity, possibly indicating that its clog is superficial. The percent increases in specific capacity reported are misleading in the sense that a 36 % increase in SW-82, for example, represented an increase from 3.6 to 4.9 gpm/ft, which is 27 % of original specific capacity. How this is interpreted depends on the validity of the starting point. As discussed in Section 7 (maintenance of Stage 3-4-5 wells), the original Q/s may have been exaggerated due to the way in which the tests were conducted.

USBR internal evaluation

Jack Cunningham of TSC provided in progress evaluation of the work (e.g., memo to Rich Demlo et al., November 23, 1998). A final post mortem was conducted during meetings held March 22 and 23, 1999 at AFO to review the overall situation, recent work, and to plan 1999 activities. As a part of that discussion, Jack Cunningham and AFO management discussed their impressions of the 1998 well cleaning work.

In general, the capabilities of the contractor in resources, science, and planning did not transfer as well as would be expected to the field site.

(1) Mobilization and logistical weaknesses started the effort poorly. Crews arrived October 10, 1998 and had 60 days to complete work (going into winter in the Valley). They were not sufficiently prepared to clean 10 wells in this time period. Rigs were assessed to be not in good condition and time was required for repairs and improvements, and during the first month, crews did not have sufficient equipment to perform the work adequately.

(2) The contractor attempted to treat numerous wells simultaneously "and spent much time chasing around unproductively" initially. A third crew was added before Thanksgiving 1998 and "thereafter things ran pretty smoothly."

(3) At this point, Jack's assessment was that the contractor "has devoted great efforts to meet Reclamation requirements and has delivered all that we required and all that we can practically expect."

At the March meeting, Jack reviewed objectives of the SOW, including maintaining chemical concentrations in wells for specified periods of time, mechanically redeveloping, and removing and neutralizing acidic discharge. Each of these tasks proved troublesome.

Maintaining pH at 2 or less required frequent chemical addition as pH levels rose quickly (as would be expected, given the hydrogeochemistry). Chemical was in the hole for as much as 48 hr., which was likely counterproductive. The Laguna report included notes by Jack Cunningham and Laguna contractors with theory and calculations on pH rebound in the wells.

Neutralization proved especially difficult, with the contractor underestimating the volumes to be removed to restore pH to 6.5. This was even though the original chemical selection (acetic + sulfamic + Layne QC-21) was selected to save on neutralizing time by minimizing acidic power (H^+ concentration). It is theorized that pockets of acidic water lodged in the hole kept pH depressed, with fresh water filling the tanks. A continuous process was finally achieved.

Summary Conclusions on Results

Based on our evaluation of follow up analysis, we suggest that

(1) Development was probably not effective on especially clogged sections of the screen, specifically the upper sections assumed to be clogged with iron and manganese oxides and insoluble salts due to cascading in the gravel pack. Intermittent surge-block development may even be counterproductive if it induces collapse of unstable units or clogs, as may have occurred in SW-150, if they cannot then be developed out.

(2) A distortion may have been introduced in that original specific capacities may have been optimistic in the first place. That is, the idealized target specific capacity ("original") is too ambitious. Withdrawal from storage may have dampened drawdown response during pumping. With clays compressed later after a period of water withdrawal, lifetime specific capacity was likely somewhat less some months after original drilling, but an exact value cannot be assigned this many years later. In any case, wells in such mixed sedimentary formations with specific capacities < 18 gpm/ft (and probably more like 10-13 gpm/ft at most) are typically prone to precipitous decline in performance over time.

(3) Concurring with Jack Cunningham, results in terms of recovered specific capacity are really all that could be expected given the SOW (which was itself a good effort given the state of knowledge). The point of the exercise, aside from cleaning wells to add capacity, was to learn what would work or not in the choices of essentially conventional methods.

(4) Improvements in treatments were needed, considering all the mechanisms at work and testing of treatment solutions on samples of clogging material experimentally under the most realistic conditions possible to:

- Improve removal of unreactive fines.
- Reduce reactive fines such as swelling clays from the gravel pack area without permanently swelling clays in situ, thus reducing formation hydraulic conductivity.
- Improve removal of oxides or hydroxides of iron and manganese and biofouling.
- Improve removal of clogging mineral deposits.

Based on these conclusions, jar testing on sample clogging material was conducted (see next section). Additionally, samples of aquifer material need to be tested for response to chemicals (e.g., clay swelling and dissolution of mineral deposits).

(5) In addition, the BCHT testing on Stage 3-4 wells (described in next section) was planned to provide additional information on what solutions and methods work, and what do not.

- At this point, we concluded that a more rapid, intense treatment (such as BCHT) may be an improvement.
- Other experience suggests that surging has to be initiated early and sustained.
- Jetting or other high-energy mechanical treatment should be used more aggressively.
- Attempts should be made to focus on more completely clogged zones instead of even movement across the screen face, as was employed in the 1998 effort. This may have to be determined by packer testing of zones.
- Some changes in chemicals are anticipated after reviewing geochemistry, and it will be useful to determine if heat will help.

(6) As discussed at length in planning the BCHT event (next section), streamlining neutralization was essential to avoid interruptions in development.

(7) As a commentary on the project documentation itself, it was Jack Cunningham's opinion that this "Final Report" is not necessarily totally accurate in representing actual field activities. It was written by someone not present. Field logs from the on-site well contractor do exist, and these logs, plus Jack's detailed supervisory logs, should be considered the more accurate information sources for future evaluation, thus they should be preserved and formalized.

For this review, it was necessary to review log information to get a more complete picture of the development activity. Recommendations for future reporting were that they should be done by someone more conversant with the methods and with first-hand knowledge of activity at the test site (as was the case in the BCHT test).

(8) There is a distinct possibility that these results were indeed "all that could be expected". The work done represents a close approximation of the "conventional" state of the art in equipment, crew skill, cold chemical use, and development time (e.g., as documented in Borch et al. 1993). Glitches in procedures and logistics in such work are almost universal, even with careful planning and in logistically less-challenging locations. Results of the more intense and systematic BCHT cleaning will illustrate if this level of effort will be necessary to bring back the 90+ Closed Basin wells with performance levels < 50 % of reported original capacity.

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Reviewed information for this chapter is supplied in the Appendix.

3. Testing of BCHT Well Cleaning Process on Stage 3 and 4 Wells

Purpose

As discussed in Section 2, the Alamosa Field Office (AFO) Closed Basin Division (CBD) seeks a definite, highly effective process that is practical to bring large numbers of wells back to specific capacity (Q/s) values that are acceptable for the project's needs. As a continuation of this effort to test the effectiveness of potential well cleaning methods, the Blended Chemical Heat Treatment (BCHT) process was tested for cleaning selected impaired wells in the Stage 3 and 4 area of the Closed Basin in August 1999, with additional well performance testing in September 1999.

The basis for this review was (1) data and analysis provided from the files and databases of the CBD, (2) site testing and observation by the author of this report, (3) onsite observations by USBR Technical Services Center (TSC) advisors to the CBD, (4) information supplied by the BCHT service provider, ARCC Inc. (working under subcontract to contractor URS Greiner Woodward-Clyde Federal Services), (5) testing information conducted and supplied by the CBD, and (6) other relevant references that contribute to background on subject.

Background

Biofouling has been identified as a primary contributor to declining performance in Closed Basin wells (see Section 1). The SOW for well cleaning for the 1998 Laguna treatments (Section 2) was oriented toward disrupting and removing biofouling deposits. The BCHT is a specific and patented (ARCC Inc., Daytona Beach, FL, USA, U.S. Pat. # 4,765,410) process, developed, starting in the late 1980s, as a means of enhancing the removal of biofouling in well cleaning (Alford and Cullimore, 1999 is a convenient reference, with the process based on earlier work, e.g., Leach et al., 1991 and Kissane and Leach, 1993). Based on past experience, BCHT (which combines heating of selected chemical mixtures and development) was identified by this author as a promising process and most likely to provide results if indeed biofouling is a principal cause of well decline.

Why this approach?

In understanding choices and the process of developing well rehabilitation treatments, it is useful to briefly consider some history. As described in Borch et al. (1993), heat was commonly used as an effective well cleaning aid in the early part of the 20th Century. Hot water was readily available on well sites as a byproduct of the common steam engine power source. With the switch from steam power to internal combustion engines in well drilling contractor equipment inventories and the availability of abundant and relatively inexpensive chemical stock after World War II, chemical mixtures, especially acids and chlorine compounds, completely displaced heat in this application. Apparent positive results were obtained in far less time.

With the great proliferation of chemical compounds in recent decades, a debate began over the relative effectiveness of various chemical choices. However, one principle stands out from this debate: the trouble in considering chemical treatment types individually is that they seldom work to best advantage alone. There is in fact, no single "magic bullet" either in chemical choices or application.

Another demonstrated principle is that chemical mixtures are most effective when accompanied by effective mechanical well development to distribute the treatment chemicals, and to dislodge and remove clogging deposits. This information is summarized in Borch et al. (1993).

Despite these demonstrated principles, an outcome of both (1) chemical proliferation and (2) the greatly increased cost of labor, is that from the 1970s onward, chemical selection and dosage was emphasized and (time-consuming) mechanical well development de-emphasized in routine well cleaning practice.

During this time, employing heat was not seriously considered industry-wide in the water well sector (although frequently employed in oilfield workover) due to equipment and power costs. However, looking for more effective treatments for difficult iron biofouling problems, Canadian researchers led by D.R. Cullimore, Regina Water Research Institute in Saskatchewan, experimented in the late 1970s with heat as a means of removing biofouling deposits from wells. While results from the work were generally encouraging, the Saskatchewan work showed some significant limitations to the use of heated water alone, including the high power input and structural problems associated with heat accumulating around well structures.

BCHT process summary

The BCHT process was developed based on a combination of laboratory and well-site studies (summarized in Alford and Cullimore, 1999) to combine the best features of both by heating selected chemical mixtures by:

(1) Choosing chemical mixtures that have been shown to be effective in disrupting and loosening biofilm deposits and then heating them to greatly increase their reactivity, and also the effect of heat in disrupting impacted biofilms.

(2) Reemphasizing the role of well redevelopment in the well cleaning process. Lengthy (by recent standards) development is employed, with an attempt to make this step as effective as possible.

BCHT is not a single process, but a phased treatment with interchangeable steps modified to address individual well conditions, which are determined through analysis. Generally, the process is described as having "shock," "disrupt," and "disperse" phases:

- The shock phase involves water-jet injection of a heated (~90-200 F) tailored chemical solution (most typically at present: acidified acetic acid amended with nonphosphate (polyelectrolyte) surfactant) into the production. The purpose is to (1) effect softening and loosening of biofouling and encrustants, (2) reduce chemical demand in the second, disruption, phase, and (3) encourage a state of physiological shock among the microorganisms by drastically altering pH and heat in their environment.

- The Disruption phase is commenced after an overnight "presoak" involving more customization, but revolves around injecting (by water-jet) a tailored chemical mixture, again heated to achieve 60 to 95 C in the well, moving the tool up and down to increase the distribution of the heated (and typically low-pH) solution, and allowing a contact time as long as possible. The pH shift is down to as low as pH 1 (but more typically pH 2). Heating increases metabolic rates at the fringe of the heat influence zone, increasing assimilation of toxic disinfectants. "Shock" and "disrupt" are typically a continuum and not distinct steps, and sometimes only involves one chemical load.

- The Dispersion phase involves optimized well development for the physical removal of the disrupted fouling material from the affected well surfaces. Standard surging methods are employed (e.g., Driscoll, 1986; Borch et al. 1993; Smith, 1995; NGWA, 1998).

BCHT equipment

In the current configuration, the specialized equipment consists of a heating-mixing rig, equipped with two polyethylene tanks (1500-gal and 500-gal) connected to two mixing and dispensing pumps, a 1 million-BTU stainless steel coil heater (oil fired) and an engine-powered high-pressure positive-displacement injection pump, mounted on a low trailer. The tank system is equipped for recirculation mixing or feeding to the heater-injector system. The coil heater was selected for survivability while heating aggressive acid mixtures.

BCHT has been employed on a variety of applications, including municipal water supply wells, pressure-relief wells with redwood-stave screens, and pumping wells at dangerous hazardous waste remediation sites. The process requires very specific knowledge of chemicals, their application, and their effects on fouling, wells, and ground water quality.

BCHT modification and augmentation

Additionally, a BCHT event may also include other specialized treatment methods and additional work to optimize well performance. For example, the Sonar-Jet process (see following), was also used on the "BCHT" test wells in an attempt to disrupt the presumed cemented clog at the top of salvage well screens (see Section 1 discussions). This type of clog is not effectively removed using BCHT alone.

The Sonar-Jet® (Water Well Redevelopers, Anaheim, CA, Pat. #4,757,663) process employs two controlled physical actions working simultaneously:

(1) A mild "harmonic" (kinetic) frequency of shock waves designed to gently loosen hardened deposits, some of which (e.g., gypsum -- identified as being present in Closed Basin sediments) are almost impossible to attack chemically.

(2) Pulsating, horizontally directed, gas pressure release, which acts to jet fluid at high velocity back and forth through well openings to clean the near-well aquifer.

Wells Selected for Treatment

Wells selected were SW-84, SW-99 and SW-103. Construction information on these specific salvage wells is included in the Appendix. Of the three, SW-84 was considered in the most deteriorated state, and SW-103 the best. They were selected to offer a range of conditions, from a low-30 % producer to better than 50 % of original capacity.

The author reviewed well video surveys conducted on May 24, 1999 by CBD on SW-84 and SW-99. The videos were recorded in color and show down and side views together (side via mirror). SW-99's record was of the screen interval only, while the video of SW-84 included the casing.

SW-84 and SW-99 video logs summary

	Depth (ft) BTC	Description
SW-84	48.7	Top of screen (erroneous 0 datum?)
	48-57	Significant soft external slime, rusty red .
	57	Heavier deposition, coats vertical rods
	59	Very heavy surficial biofouling
	62	Biofouling deposition becoming thinner
	66	Very clean. Sand grains visible
	68-total depth	Rods very clean. Lots of well "snow"
	88.6	Camera encounters soft in-fill.
SW-99	Start to 32	Pitted casing
	34.7	top of screen, extensive surface deposit.
	37	Slots obscured, looks soft
	47-50	Possible rod corrosion
	57	Screen totally obscured by biofouling deposition
	58	Dark-colored deposits
	59-total depth	screen totally clean in appearance
	88.8	slime in sump.
		After brushing: Cleaner screen at the top. Some deposits left in the 50-ft screen interval.

From a collective discussion through the spring of 1999 (involving AFO and TSC personnel, the author and ARCC's George Alford), the possibility of an impacted, geochemical clog in the upper screen zones of these wells, formed due to the persistent drawdown into the screens under the prevailing geochemical conditions, emerged as an important issue. The video (which only shows what is visible in the well) does not contradict this theory, and supports the idea that clogging is worse in the interval where the pump is set.

It was proposed by the author and Alford that Sonar-Jet be used to loosen the suspected hardened material. It was decided by USBR to use it on SW-84 and SW-103 initially, with SW-99 treated by BCHT heated chemicals and mechanical development only.

Nature of Well Clogging Material and Chemical Effects on the Material

As a function of this research, the author experimented with solutions to dissolve and suspend material in well rehabilitation, using jar testing. It has to be emphasized that these are not wells, which are more complex, but a way to directly and rapidly compare some solutions for disrupting known clogging material. As raw material, CBD supplied solid material removed from well pumps in SW-99 and SW-103.

Analysis of clog material

The SW-99 material was bright rusty red, and under light microscopy (normal light, 400 and 1000x), consisted of abundant apparent Fe oxide particles and biological "iron bacteria" filaments. See Section 4 for a discussion of methods for analysis of these materials. The SW-103 material was dark brown (otherwise the same in texture), possibly heavier in Mn oxides.

SW 99	Abundant spiral thread fragments (presumed *Gallionella* spp. with abundant amorphous, apparent iron oxide particles. No other filament structures visible.
SW 103	Abundant dark brown amorphous particles, small-diameter presumed *Gallionella* sp. fragments, rare lighter brown particles and some flat filament fragments, however no structure indicating *Leptothrix* or *Sphaerotilus* sp., possibly Actinomycetes.

Quantitative and semi-quantitative elemental analysis of solids samples was conducted at the Ohio State University Microscopic and Chemical Analysis Research Center in June 1999. Results are attached in the Appendix. Summarizing:

	SW 99	SW 103	
Fe	28.6 %	15.6 %	wt/wt %
Mn	0.48 %	17.7 %	wt/wt %

Other major constituents were N, P, Mg, Si, and Li. These results tended to confirm the preliminary conclusion, based on microscopy, that SW-99's pump clog was dominated by Fe oxides and SW-103's pump clog had a significant Mn content. Presumably, the large fraction of "lost" material was organic in nature. This could be defined using a loss-on-ignition test. These analyses do not suggest a mineralogical clog (beyond deposition of the Mn and Fe salts), assuming that the pump clog was similar to the formation clog.

Jar testing for treatment removal of clogging solids

Samples of solids received in May from AFO as described above were subjected to treatment by a range of chemical solutions in an array of three jar tests (300 mL with magnetic stirrers). In each test, a 300-mL solution was made of Ada, Ohio tap water (0.1 % free chlorine and ~ 160 mg/L total Ca hardness) and chemical mixtures to be tested. These were then loaded with 10 g of test solids (wet) and permitted to react while stirring gently. Tests were conducted at ambient water temperature (~ 26 C) of the laboratory tap.

At the time of these tests, reagent-grade HCl (37 % assay) and acetic acid (99 %) were available as acidizing agents. The product Citranox (Alconox Inc.) was used as a surrogate polymer wetting agent. This product has properties similar to QC-21, used in the 1998 Laguna tests, being acidic (1 % solution pH 3.2) in contrast to CB-4 (Calloway Chemical, ARCC Inc.), used in the BCHT tests, which is mildly alkaline.

Solutions tested were:

- Citranox 1 % (analogous to the QC-21 used in the Laguna trials, Section 2)
- HCl 5 % alone, HCl 5 % + 1 % Citranox, HCl 2.5 % + 1 % Citranox.
- Acetic 5 % alone, Acetic 5-10-15 % + 1 % Citranox.
- Acetic as above, acidified to pH 1.5.

Results and likely impacts:

- Generally, 2-5 % HCl dissolves the SW-99 material quickly and completely, but a pH 0.5 - 0.8 solution in the well at the end of 8 hr + would require considerable neutralization (e.g., as occurred during the Laguna treatments) and poses a safety risk without improving well-cleaning performance.

- Acetic acid mixtures yielded suspended clog particles and reduced particle size, but did not dissolve material significantly. Without acidification, acetic rebounds to pH 3 to 6.
- The SW-103 material did not dissolve in 5 % HCl, but was completely oxidized and reduced to very small, weathered particles.
- The acetic dispersed and suspends the SW-99 material pretty well, except for a recalcitrant residue (heavy iron oxides and silt). The solution concentration (5, 10, or 15 %) was not especially important, with the only difference being end pH, which would affect neutralization.
- The need to keep material in motion throughout a treatment is apparent.
- Iron "bbs" and large metal oxide plates formed during HCl treatment, if not completely removed, could be packed into the aquifer formation, reducing effective porosity.

Field Demonstration of BCHT

Well pre-testing

A pre-treatment well step test was conducted on SW-99 by the author and Jack Cunningham (TSC) on August 8, 1999. Pretesting of SW-103 was not possible at that time as desired by the author, as the well was connected to service, and SW-84's pump was removed. Results of the SW-99 pretreatment test analysis are included in the appendix.

SW-99: The SW-99 test was conducted using the CBD's 6-in-diameter turbine flowmeter (McCrometer) apparatus (sketch illustrated in author's field notes attached in Appendix) and author's electric water level probe (Global model, 300-ft tape). The Goulds 25-hp 3 stage well pump was set on column pipe at 65 ft below the flange (1.37 ft above hatch base). The pump was attached to the flowmeter using 4-in. rubber armored hose.

The test, started at 1241, was conducted at 50, 100, 150, 200 and 250 gpm, with each step run to stability. Summarized results:

Flow rate (Q) in gpm	Final step drawdown (s) in ft	Calculated Q/s (gpm/ft)
50	11.4	4.4
100	21.1	4.76
150	29.7	5.05
200	37.5	5.33
250	47.5	5.26

Analyses were conducted using methods described in Kruseman and de Ridder (1994), which are standard step-test well performance analyses. A problem in analysis became apparent when 1/Q/s vs. Q (Hantush-Bierschenk method) was plotted on arithmetic scale. It was apparent that the flowmeter information was erroneous for rates below 200 gpm. The numbers for the 200 and 250 gpm steps were used for test analysis, and the 5.26 gpm/ft Q/s value acceptable as a pre-treatment benchmark (although not considered acceptably accurate for hydrologic analysis). Overall well efficiency remains at about 95 % (as reflected in the rapid stabilization of drawdown at each new step).

For comparison, step test data from July 1983 (construction) were plotted and analyzed (as provided in Appendix). This test was conducted at rates unsustainable at the present time (166-675 gpm). Q/s at 675 gpm was 13.5 gpm/ft, and well efficiency was also about 95 %.

Comparison of SW-99 test analyses:

Parameter	1983 tests	1999 tests
Specific capacity	13.5 gpm/ft @ 675 gpm	5.26 gpm/ft @ 250 gpm
Well efficiency	95 %	95 %
Well loss (as % of drawdown)	11 % @ 250 gpm	12 % @ 250 gpm
C (nonlinear loss coefficient)	C = 1.28 x 10^{-5}	C = 9.24 x 10^{-5}
B (intercept) linear coefficient	B = 0.06425	B = 0.167

Notes on analyses and comparisons: Due to the problem with flow measurements in the 1999 test, only two curve points were available for plotting the C slope and B intercept, so these may be off (results of the May "self-step-test" results suggest the curve is steeper). The test does indicate near-well (nonlinear) and near-formation (linear) losses may have increased, reflecting clogging. The well losses are low and remain low, probably reflecting overall screen efficiency (recall the nearly 30 ft of apparently clean screen in the video). One high-probability explanation of the difference in the Q/s values (given the low differences in well performance parameters) is reduced saturated thickness. The static water levels are significantly lower than in 1983, and Q/s can directly reflect changes in formation transmissivity (conductivity x thickness calculated as ft^2/d) if thickness changes, even when conductivity (ft/d), which is affected by well clogging, does not change.

Along with taking water level measurements, BART tubes (see Section 4) were inoculated at the end of the test: One each IRB (iron-related bacteria), SLYM (slime forming bacteria), DN (denitrifying bacteria) and SRB (sulfate-reducing bacteria). Results:

IRB	4 days	These results suggest that biofouling is present and active, with
SLYM	2 days	slime-forming bacteria very active and IRBs moderately so. DN and
DN	negative	SRB are inactive, indicating that the near-well environment is high-
SRB	negative	redox-potential.

SW-84 and SW-103: Pre-treatment specific capacities (Q/s) for SW-84 and SW-103 were roughly approximated using database information on yield and unconfined water level (UWL) for SW-84 and the elevation of the low-level cutoff for SW-103. SW-103's water level instrument had been inactive for some months so UWL data were not available. This is a test condition that should not be tolerated in future efforts.

A pretreatment rough approximation of Q/s for SW-84 was 2.9 gpm/ft (using the latest data) and SW-103 12.1 gpm/ft. "Self-step-test" data for SW-103 yielded what seems to be an anomalously high Q/s of > 18 gpm/ft. Flow, SWL and PWL should be reviewed. It is emphasized that these are approximations, and that this type of indirect determination of Q/s is not lifted up as a procedure to be relied upon without further confirmation. Separation of well screen, near well, and aquifer effects was not possible.

Features of field trials of BCHT in Closed Basin

Treatment goals

Based on flow history and probable actual Q/s (Q/s_a), SW-84 was projected to be capable of Q =180-360 gpm at Q/s = 7 gpm/ft with a PWL at top-of-screen, SW-99 was projected to be capable of Q = 250 gpm at Q/s = 8 gpm/ft with a PWL at top-of-screen, and SW-103 projected to be capable of Q = 450 gpm at Q/s = 15 gpm/ft with a PWL at top-of-screen. These were preliminary goals. The rationale for Q/s_a is discussed in Section 7, but in summary, as discussed in Section 2, it is suspected that recorded values for original Q/s were exaggerated, and a value was estimated based on Q histories of numerous wells.

Treatment procedure summary narrative

BCHT began on SW-99 on August 11, 1999. Pre-treatment ambient well pH was 7.9 and temperature 57 F (bailed sample, measured with Orion hand instrument by Smith). Based on the pre-treatment review, two loads of approximately 1000 gal. each were planned. The first load was as follows in 1000 gal. of SW-99 well water: 3-1/2 55-gal. drums of glacial acetic acid, 4 50-lb. bags of sulfamic acid and 300 lb. (2 x 150-lb carboys) of Arccsperse CB-4 (Calloway Chemical, ARCC Inc. proprietary nonphosphate wetting agent), mixed in tank with a final preload pH of 1.9.

The heater was started and fed at an injection pressure at the pump of 500 psi and temperature of 200 F (~ 11 gpm). The load was approximately 18-20 gal. of chemical per foot of screen, with chemical fed from the bottom of screen to the top. At the end of chemical loading, bailed sample pH was 3.1 and temperature 73 F (below Mr. Alford's desired temperature).

By morning 8/12/1999, well temperature was 53 F and pH 4.3. The second mix was made using canal water (not optimal, but the only water reasonably available). It was expected that the chemicals and heat would destroy microorganisms brought from the canal. The chemical mix of the previous day was repeated except that only 14-18 gal of CB-4 was used. At the end of mixing, tank pH was 1.6. Injection conducted as before. Chemical dosage was concentrated in the top 10 ft of screen, assuming the clog was concentrated there. The bailed sample yielded a temperature of 105 F and pH 1.6. A second bailer yielded 111 F. This was left over night.

On Friday, 8/13/1999, development tools were readied. A tool as described in Jack Cunningham's notes of 8/13 was installed. The tool was sized for a 10.55-in. well screen I.D. as reported in records. Rubber trimming was needed, but the tool still stuck in the top of the screen. Apparently, the screen was a standard Johnson model, which at this screen and rod size has a 10.375-in. I.D. The surge block plates had to be turned down at the machine shop. Development commenced Sunday 8/15/1999.

Pumping with development proceeded on Monday, at Jack Cunningham's calculated rate of ~55 gpm (average). Rig stroke length was 5 ft and speed 1 ft/sec. pumping to neutralization in 21,000-gal. hired "frac" or Baker tanks using soda ash for neutralization. A total of 8,820 gal. were removed from the well, leaving a well pH of 6.5. An approximate total of 14 hr of actual development was conducted prior to pump re-installation.

Preparations at SW-84 commenced August 19, 1999. A pumping test was conducted by CBD maintenance personnel with indeterminate results (140-150 gpm and drawdown "to top of screen" ~42 ft, depending on measuring point). A "before" Q/s was therefore about 3.33 to 3.5

gpm/ft. The screen diameter was checked and 13 in. I.D. (Johnson) was recorded. A treatment mixture was made as before (193 gal. glacial acetic, 50 lb. sulfamic, 12-15 gal. CB-4 in 1000 gal. water) with final mixed pH of 1.4. The CB-4 and sulfamic were reduced based on Mr. Alford's observations during the SW-99 treatment. This mixture was fed in at 202 F, ~ 500 psi (gauge damaged) and about 9 gpm. The BCHT jetting and surging block was equipped with 13-in. dia. surge plate for this screen. At the end of dosing the well (3:28 pm, 8/19/99), the bailed sample well pH was 1.4 and temperature 132 F. A second such mix was made on 8/20/1999 and fed in at 200 F and 9.2 gpm as before. At the end of loading, well pH was 1.7 and temperature 134 F (bailed sample).

On Friday, August 20, 1999, an Am-West Inc. (Brighton, CO) crew arrives for Sonar-Jet treatment. Treatment of SW-103 (not yet treated with BCHT) was commenced. According to the crew, a "-1" load was selected (mildest Sonar-Jet classification, what this means is proprietary). The tool was lowered to the bottom and three thumps heard, according to Jack Cunningham's notes (charge 50-1). then next 10 ft of screen and 29-39 ft (charge 10-1). Three thumps each time. This treatment was completed in two hours.

At the end of BCHT loading on 8/20/1999, SW-84 was treated with Sonar-Jet. The interval 50-100 ft below the extension and the 45-50 ft interval were treated. This treatment was completed in one hour. Jack Cunningham's notes for 8/20/99 illustrate the Sonar Jet string.

SW-84 was developed at 30 min. per screened interval, using stroke length and speed as before, and pumped using airlift. Total time is unrecorded in USBR notes.

Because of concerns about swelling clays at SW-99 and SW-84, treatment at SW-103 was changed (a typical BCHT feature). The concern was that CB-4 and acidic solutions left in long contact with these clays would cause swelling and mobilization. This theory is based on Canadian studies (see PM plan for Stage 3-5 wells) and experience of Mr. Alford and others as described in his report, but that this mechanism is operating is unconfirmed.

On Wednesday August 24, 1999, the new chemical mix was formulated: (in 1000 gal. water) 0.1% solution of CB-4 (1 gal.), 8 oz. (volume) of sodium hypochlorite, 8 oz. sodium bicarbonate (100 % baking soda). The pH was adjusted from 8.3 to 7.3 using ~ 240 mL (1 cup + 3 Tsp.) of solid sulfamic acid. This was injected at the usual temperature and pressure. On Friday 8/27/1999, morning well temperature was 47 F at 70 ft in well depth (from top of treatment riser). A second batch was mixed as before. The end well pH was 7.3 and 120 F. The well was brushed and subsequently developed and airlift pumped. Total time is unrecorded in USBR notes. Based on ARCC's report, about 16 hr of surging was invested.

Changes in well performance

Post-treatment step tests were conducted by CBD (data sheets and analysis attached). Updated flow and UWL data were used for comparison (also attached).

Salvage well	Pre-treatment Q/s (1)	Post-treatment Q/s (2)	Post-treatment Q/s (3)
84	2.9	7.3	ND (4)
95(5)	3.3	6.3	1.7
99	5.3	7	1.4
103	12.1	15.45	13.5

(1) These are approximations as tests were not accurately conducted. CBD and not BCHT treatment.
(2) CBD-conducted step tests. (3) From telemetry database.
(4) No useful post-treatment flow and UWL readings. (5) CBD, not BCHT methods.

The CBD step tests used the same flowmeter apparatus employed during the SW-99 pretreatment test (which was demonstrated earlier to be inaccurate at the flows being tested). Drawdowns were measured using the facility's M-scope. Measurements were taken approximately once per step, so that it was not possible to determine if the steps were run to a stabilization point. Charting of 1/Q/s vs. Q illustrated that the flowmeter was again inaccurate at flows below about 250 gpm. Of the four tests, a Hantush-Bierschenk Analysis (Kruseman and de Ridder, 1994) was possible for two-point curves for both SW-95 and SW-103 (but unfortunately not for SW-99). These two-point slopes are not reliable and testing should be repeated to provide a more valid analysis. However, the "after" well test Q/s values are probably "in the ballpark" if not accurate. The accuracy of the telemetry data should be verified, in that such a rapid loss of Q/s is unlikely. The flowmeters may be underreporting flows.

Summary and Recommendations

(1) Positive results were obtained from this "BCHT" (BCHT+Sonar Jet) cleaning trial:

SW-84 improved from Q/s = ~2.9 (approximated using file cfs and UWL) or 3.3 (brief pretreatment test) to 7.3 gpm/ft (CBD test).

SW-99 improved from 5 to 7 gpm/ft despite the problems and set backs.

SW-103 (again, the before value is heavily derived, using database information) Q/s = 12.1 improved to 15.45 gpm/ft (CBD test).

It is important to note that these are all approximations due to uncorrected inaccuracies in the testing program.

(2) Truly valid assessments of treatment results require valid pre- and post-treatment well pumping tests. Flow meters or orifice weirs sized to the well output are needed, and valid step testing procedures followed. An apparatus to make such testing easier is described in the Stage 3-5 maintenance plan. These procedures and their analysis are previously described and in several of the supplied references. It would have been most useful if the BCHT and Sonar-Jet components of the well improvements could have been separated out. An opportunity for this may exist if pumping tests are conducted using valid procedure before and after a proposed Sonar-Jet treatment of SW-99.

(3) Some variation of BCHT, augmented with Sonar-Jet as indicated, is a viable rehabilitation method for maximizing Q/s in difficult-to-treat wells. Results obtained in 1999 were similar to or better than 1998 with much less field time invested. In general, a "cold" chemical and development maintenance seems possible. These are discussed in the Section 7.

(4) Also, based on this experience, a chemical mix choice selection is forming. Further laboratory scale tests are needed to determine if switching from an acidic, heavy wetting agent solution to a mild wetting agent solution at neutrality is really recommended. The laboratory tests should observe effects on realistic clog materials, preferably from well cores as proposed.

(5) Water supply for treatment has to be addressed. Canal water is not optimal. It adds biological variables that may, or may not be controlled chemically. Access to a good well supply is preferred, unless on-site filtration of canal water is conducted.

(6) Personal and procedural commentary: USBR personnel, specifically permanent, long-time CBD personnel and TSC personnel likely to be involved in providing advice and oversight, should be trained in and highly familiar with the BCHT procedures, as well as well testing and other associated methods. A factor that cropped up in the August BCHT trials is what the author will characterize as "clash of cultures:"

ARCC (George Alford)	USBR/AFO
Mr. Alford is colorful, action-oriented, and accustomed to solitary decision-making on the job site without second-guessing by others. While ARCC Inc. has experienced no time-loss accidents or recorded adverse environmental impacts employing BCHT, job-site safety procedures are casual. This is a reflection of the inherent low risk posed by the organic acids typically used.	Safety and systems oriented, which permits an environment of safety and compliance regardless of individuals or agency units involved, but can be somewhat inflexible. Professional oversight of job sites is assumed. All new procedures scrutinized and questioned. Somewhat collective decision-making. Plans and record-keeping emphasized and enforced.

This author's own personal observations, discussions with Mr. Alford and USBR personnel, and a review of Jack Cunningham's field notes reveal this personal friction factor. Mr. Alford has demonstrated extensive personal accomplishment in this field and success with the procedure in many applications, however, his personal style can lead to friction with a more systematic or (in some views) bureaucratic decision and management structure. On its part, as Rich Demlo noted, safety and environmental compliance is the personal responsibility of the AFO management, and a systematic approach to these aspects of the well-cleaning job helps to assure success.

Based on this assessment, it is the author's recommendation that USBR learn the BCHT system, but take its application on site in the Closed Basin under the structural and procedural routines of the AFO. At present, ARCC Inc. chooses to retain its heater rigs under its direct control to assure their maintenance and operational readiness. The modalities of such an arrangement would have to be negotiated.

(7) Reasonable (but not spectacular) results on recoverable wells (see Stage 3-5 maintenance plan triage) can come from a fairly rapid and effective combination of Sonar Jet and a BCHT-type treatment (in some configuration). If these wells are then maintained rigorously and demands on the CBD's water kept at sustainable levels, yields can be sustained.

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Also files kindly supplied by Ella Mae Herrara and the AFO staff, whose work on accessing, organizing, interpreting and charting this vast and complex data set is gratefully acknowledged. Also gratefully acknowledged is John Ellis and Jack Cunningham for sharing their observations and field notes, Brent Keevil, Droycon Bioconcepts, and George Alford, ARCC Inc., for input on the evaluation of BCHT treatment chemical mixture and development results, and the Ohio Northern University Chemistry and Biology Departments for support in jar testing.

Section Attachments: Photos of treatment features

Located in the Appendix:

SW 84, SW 99, and SW 103 Information

(1) Construction and background performance information
(2) Test and analysis information, SW-99 pre-treatment step test
(3) Test and analytical information, CBD-conducted SW-84, -95, -99, and -103 post-treatment step tests and flow data.

Clog treatment analytical Information

(1) Elemental and mineralogical analysis of SW 99 and SW 103 solids
(2) Jar test detailed results

Field notes from August 1999 BCHT field demonstration and testing

(1) Jack Cunningham, TSC
(2) John Ellis, TSC
(3) Stuart Smith (Smith-Comeskey)

4. Annotated Bibliography of Biofouling Monitoring Tools with Potential for Monitoring Deterioration of Closed Basin Salvage Wells

Purpose

As discussed in the first section, deterioration of Closed Basin salvage wells apparently has multiple contributing factors, one of which is biofouling. These phenomena have already been extensively studied and biofouling is accepted as a significant factor in well clogging in Closed Basin wells. On a more general level, Smith (1992 and 1995), Cullimore (1993), Howsam et al. (1995) and McLaughlan (1996) are currently available publications that review the range of biofouling mechanisms in wells. These publications are discussed further in the following.

It has been amply demonstrated (Sections 2 and 3 and other history) that no single selection of treatment method will restore salvage well production, and that preventive maintenance (PM) treatments guided by long-term evaluation will be necessary.

One identified need in PM is to preventively monitor for biofouling. The Alamosa Field Office (AFO) Closed Basin Division (CBD) has expressed a desire for a biofouling methodology that is both capable of detecting changes in biological activity and biological accumulation in time to schedule effective treatment, and that is capable of being used routinely in maintenance operations. This section is intended to provide an annotated bibliography of existing and relevant printed and unpublished literature as part of the theoretical basis for this effort.

Conceptual and Methods Background for Biofouling Monitoring of Wells

As with physico-chemical analysis, biological monitoring comprises sampling and analysis of the contents of samples. The appropriateness of both activities affects the validity of the results of the monitoring activity.

- Samples must be collected in such a way that biofouling indicators are detected, and detected at a level that permits a practical response.
- Analytical methods should be able to provide a way to detect, and in some fashion, quantify the biofouling components present.

For the purpose of biofouling analysis for treatment (specifically for the selection of chemical treatments), the analysis is most effective when the chemical and mineralogical components are analyzed along with the microbial.

Choosing parameters for biofouling monitoring in preventive maintenance monitoring

Historically, microbiological analysis of the extent of biofouling has been used mainly as a diagnostic tool for wells that have already experienced noticeable pumping, water quality, and other problems. Only in relatively recent times has monitoring for preventive maintenance been considered as a practical way to assess the (1) extent of biofouling, and (2) potential for future biofouling. Both analytical and sampling methods have been inadequate until very recently for the purpose of preventive maintenance monitoring (Smith, 1992).

There are published methods for "iron bacteria" and related biofouling sampling processing analyses that carry the weight of consensus standards: *Standard Methods for the Examination of Water and Wastewater* Section 9240 (APHA, AWWA, and WEF 1998) and ASTM Standard D

932. However, the methods published in Section 9240 have not been updated for many years to reflect improvements in practice. Significant updates have been accepted for the Supplement to the 20th Edition. It has been our experience that these methods are inexact and tend to provide false-negative results (e.g., Smith, 1982). Additionally, the culturing methods described tend to require the support of a full-scale environmental laboratory. Commitment to such support to analyze samples for "iron bacteria" and other biofouling microorganisms is not common in North America. The AFO is fortunate in having a laboratory nearby in Sangre de Cristo Laboratories that will conduct such sampling and analysis.

Conceptual frameworks for developing improved methodologies to monitor and predict biofouling in wells have been presented in conferences on the subject in the mid-1980s to early 1990s. Wojcik and Wojcik (1987) and Gaffney (1987) summarized the philosophy of monitoring for biofouling and recommendations for monitoring to detect or "predict" it in a qualitative fashion. Their recommendations are incorporated in the comprehensive recommendations of Borch et al. (1993) and iron biofouling recommendations in Smith (1992). Cullimore (1990a,b) provides an alternative based on specialized biological testing methods summarized in Cullimore (1993) and evaluated by Smith (1992) among others. McLaughlan et al. (1993) provides examples of a research study specifically designed to study in detail fouling and corrosion in wells. PFRA (1999) is another illustration of the use of biofouling monitoring in a study on the field scale.

Physical-chemical parameters for analysis

There are a number of factors that contribute to plugging and other problems associated with biofouling. The occurrence of specific levels of microbial nutrients, electron acceptors, or metabolites (C, H, N, P, S, O, Fe or Mn in various forms) has been suggested for predictive monitoring (Cullimore 1987, 1990a), but much more work needs to be done before chemical constituents can be used to construct models for biofouling potential.

Dissolved oxygen has been suggested to be a limiting factor in the rate at which biofouling buildup occurs in a well. Using model wells, Mansuy (1986) demonstrated that plugging occurred much less often in anaerobic models than it did in highly oxic models. However, there are too many variables involved in iron biofouling to make any useful predictions based on oxygen content alone.

Several investigators have recommended redox potential measurements in combination with pH measurement for routine monitoring purposes and as indicators of potential plugging problems. Armstrong (1978), Clarke (1980), and Borch et al. (1993) describe methods for using redox potential measurements for making assessments of the well environment.

Redox potential measurements reflect the relative ratio of oxidized and reduced species of Fe, Mn, S and other minor constituents in the water sampled. Elevated redox potential levels indicate an environment in which oxides of Fe(III) and Mn(III-IV) are precipitated, which could result in increased plugging. The redox potential is a generalized measurement of the well environment and cannot by itself identify the responsible ion pairs and microenvironments present in the well (Smith, 1992; McLaughlan et al., 1993). For example, MnIV oxide precipitation can occur in ground water with bulk Eh readings far below the +600 mV value at pH 7 indicated by Hem (1985) as the threshold for MnO_2 and MnOOH stability (the actual minerals formed are chemically more complex). Such oxidation and precipitation is attributed to surface enzymatic activities of *Leptothrix* spp. bacteria in Mn-depositing biofilms (Tuhela, Carlson and Tuovinen, 1997). However, over time, patterns can emerge. For example, results of Eh analyses by Smith (1992) in three wellfields, when plotted on scatter diagrams, were generally consistent with the pattern of biological activity. It is probably these activities driving bulk redox potential and not vice versa.

Microscopic examination and analysis

Microscopic examination of water samples as well as metal oxide biofouling encrustations can reveal stalk and sheath fragments of bacteria presumed to be involved in iron biofouling. Therefore, light microscopic examination has traditionally been the method of choice for confirming and identifying iron bacterial structures. APHA, AWWA, WEF (1998) and ASTM D 932 document the commonly used procedures for sampling and analyzing samples by light microscopy for "iron bacteria." However, a weakness in relying on microscopy alone as an analytical tool is that, in many instances, iron biofouling may be difficult to identify if the biofouling does not include the filamentous or stalked bacteria (a common occurrence).

On the other hand, light microscopy provides information on nonmicrobial biofilm or deposit components that is not available from cultural analysis:

- The characteristics of metal oxide or mineral inclusions can be determined in a preliminary fashion so that further decisions on analysis (e.g., mineralogical) can be made.
- The overall characteristics of the biofouling mass (and changes in characteristics compared to past analyses) can be observed.
- In addition, light microscopy reveals microorganisms present that would not be identified through biochemical means (e.g., diatoms or protozoa) that add to clogging or environmental health concerns.

The optical resolution necessary for observing bacterial structures is based on 400X and 1000X magnification (40X dry or 100X oil-immersion objective + 10X ocular) with a direct electric light source. Most microscopes available in laboratory settings are routinely equipped with maneuverable stage calipers, micrometer readings on the focusing knobs, and a micrometer scale in the ocular; and can be equipped with a camera attachment, which permits the recording of observations. Phase contrast and epifluorescent methods are useful enhancements for light microscopy, but not necessary for biofouling diagnosis. Electron microscopy provides ultrastructural details of specimens but is purely a research tool in the study of biofouling.

An available semiquantitative maintenance monitoring method using microscopy was described by Barbic et al. (1974) and updated in Barbic et al. (1990) -- based on experience with the Belgrade, Yugoslavia ground water supply.

- Numerous immersed microscopic slides are observed for signs of biofouling (filaments, stalks and other identifiable structures).
- An index is expressed based on (1) the number of slides that exhibit attached bacteria or particles and (2) the density of attachment.
- While providing a numerical index (that can be analyzed mathematically), the Barbic et al. methodology for assigning an index value is by nature (1) dependent on the judgment of the individual microscopist and (2) quite time-consuming. However, it demonstrates that this monitoring is possible with relatively simple tools if organized and used consistently.

Culturing methods for biofouling analysis

APHA, AWWA, and WEF (1998) Section 9240 presents several formulations for nutrient media for heterotrophic iron precipitating bacteria, Mn-oxidizing organisms, and for *Gallionella* enrichment (for example, as employed by Sangre de Cristo Laboratories). Media for iron precipitating bacteria have been used with mixed success. No effort has been made to standardize these media with reference cultures from well water systems and thus the recovery efficiency of iron bacteria from groundwater samples remains unknown at the present time (Tuhela et al., 1993). Some media, notably the Wolfe's medium for *Gallionella* enrichment, are difficult to formulate properly. The Fe source for oxidation is FeS, which must be prepared, and the supernatant water must be saturated with carbon dioxide.

A number of attempts have been made to improve existing cultural methods. Cullimore and McCann (1977) devised a medium (W-R medium) which was based on citrate as the sole organic carbon source. A variation of W-R medium is available as a dehydrated kit form (IRB-BART™, Droycon Bioconcepts, Inc., Regina, Saskatchewan) and as a prepared solution (BPOM-MAG, MAG Ltda., La Plata, Argentina). The W-R medium and its derivatives were developed to recover microaerophilic iron and manganese precipitating microorganisms. Both IRB-BART and BPOM-MAG (BPOM = bacterias precipitantes y oxidantes del hierro) tests have been presented as a method of detecting growth to provide a presence-absence (P-A) or semiquantitative (MPN) result (Mansuy, Nuzman, and Cullimore 1990; Gehrels and Alford 1990; Gariboglio and Smith, 1993).

Smith (1992) field-tested a similar medium (R2A-FAC, prepared R2A agar medium amended with ferric ammonium citrate) in an attempt to differentially culture and count FeIII oxide-precipitating colonies. A variation was R2A amended with $MnSO_4$. Results were ambivalent, but possibly relevant to the Closed Basin, as (1) R2A-FAC was prone to being overrun with Actinomycetes when inoculated with samples from Ohio River Valley alluvial wells and (2) researchers (Colin Charnock, Oslo, Norway, pers. comm.) had good success recovering Mn-precipitators.

Downhole camera use in well biofouling analysis

While not a microbiological method, per se, color borehole camera surveys offer useful information on the type and location of biofouling deposits within the range of view of the camera. While biofouling deposits may be identified with monochrome cameras, color permits an informed observer to make valid conclusions on biofouling type. Being able to observe variations and locations of visible deposits permits more precise decision-making on treatment strategies.

The camera's effectiveness is limited to its field of view. "Deep-seated" biofouling deposits in the filter pack and formation are not observable this way, and have to be detected using indirect means such as culturing and physico-chemical analyses. While such studies are rarely printed, McLaughlan et al. (1993) is a recent example of a study using the camera as part of well biofouling analysis.

Sampling for biofouling monitoring: Selection rationale for obtaining samples

Grab samples can be collected by pumping, or biofilm material allowed to collect on in-well coupons or wellhead filtration devices.

<u>Grab sampling</u>

Pumped (grab) sampling is the easiest way to obtain samples from wells for analysis, including analysis for evidence of biofouling. This method assumes that biofilm bacteria and their

characteristic structures are also present in the water column (planktonic phase). This is always a qualified assumption. The absence of bacteria in samples taken this way may simply mean that the bacteria are attached, not that they are actually absent in the well.
Pumped samples may be analyzed by microscopy, culturing with selective or general purpose nutrient media, and potentially by other biochemical means. Among the potential limitations of pumped sampling is the "snapshot" nature of the samples, which represent the water quality only at the time that the sample was taken. Shedding events may provide slugs that transiently increase microbial counts or the concentration of iron and manganese water. Most bacteria in pumped water samples under these circumstances have been sloughed off the attached biofilm, and represent only a tiny fraction of the population and diversity of organisms that comprise the biofilm.

After a period of sustained pumping, biofilms will yield very little of the turbid material for microscopic examination. Samples taken after prolonged pumping may fail to detect the presence of chemical and microbiological parameters that would indicate the presence of biofilms. Filtration or centrifugation as recommended in *Standard Methods* increases the odds of recovery of material useful for microscopic identification. Improvements in the sampling further enhance the odds.

Cullimore (1993) describes a time-series pumped-sampling procedure (similar to familiar procedures for ground-water quality analysis) that attempts to overcome the randomness of grab sampling. Cullimore's procedures involve taking advantage of the phenomenon that biofilm detachment occurs preferentially on start-up after a period of rest. The pump is shut down for 2 hours to several days to permit the biofilm to reestablish. Samples may be taken:

(1) just prior to shut-down,
(2) immediately after restart,
(3) a few hours later, and optionally,
(4) some days later.

This approach, which includes taking replicates of samples at each sampling step, helps to overcome the statistical limitations of random pumped grab sampling for culture analysis. This information can be used in making an assessment of the microbial ecology in the well and the aquifer adjacent to the well according to Cullimore (1993). In addition to the time steps, analysis of samples taken at various points in a ground-water-source system permits the development of a profile of the microbial ecology of the system.

Surface-collection methods

Surface-collection methods provide a different procedure for detecting bacteria involved in biofouling phenomena in the well bore and at the wellhead. These methods overcome some of the shortcomings of pumped grab samples by providing samples of intact biofilm and usable volumes of material for microscopy or other analysis.

Collection surfaces can be placed at various locations in the water system. For collection of well biofilm samples, collectors may be placed directly in the well bore or in the water pumped from the well. The primary considerations for choosing in-well and/or wellhead collectors are (1) representative collection of biofilm samples, (2) access to the well for collection, and (3) influence of the collector on well performance.

Several experimental designs for collecting biofilm organisms have been presented in the literature. Hässelbarth and Lüdemann (1972); Wojcik and Wojcik (1987); Hallbeck and Pedersen (1987); Howsam and Tyrrel (1989); and Smith and Tuovinen (1990) all describe in-well and side-arm immersed-slide collectors of various types for the collection of iron biofilms. These are based on even older concepts. McFeters (1987) describes the use of side-arm membrane filter cartridges for collecting bacteria in water, and Howsam and Tyrrel (1989) have developed a trickle-through sand filter (called a moncell) for collection of biofilm samples. Additionally, any effective filter collector, such as the assembly developed for *Giardia* and *Cryptosporidium* sampling (U.S. EPA, 1995) can be used.

In-well biofilm collectors are practical only if there is access to the well bore itself through the well cap or nearby water-level monitoring wells (piezometers). An in-well collector has to avoid hanging up on submersible pump wire or other obstacles. The inserter devices refined by Smith and Tuovinen (1990), as described in Smith (1992), are designed for tight wells with submersible pumps.

Wellhead devices allow collection even on wells which are permanently sealed at the surface. Howsam and Tyrrel (1989), Hässelbarth and Lüdemann (1972), Hallbeck and Pedersen (1987) and McFeters (1987) developed sampling devices specifically to collect bacteria and well fouling material at the well head. The flowcell system used in Smith (1992) and accepted for inclusion in the Supplement to the 20th edition of *Standard Methods*, was designed to collect intact biofilm samples with minimal oxidation from the discharge of wells that lack sufficient access to the well bore to install in-well collectors. The U.S. EPA (1995) device or any conventional iron cartridge filter can also be used, but biofilm then has to be extracted from the cartridge.

Representativeness of collection sampling

Since biofilm communities are unevenly attached on immersed surfaces, there is a question of the representativeness of biofilm sampling. Glass and polycarbonate slides have been used for in-well collectors in a variety of work (e.g., Smith and Tuovinen 1990; Hallbeck and Pedersen 1987). Although their surface characteristics are somewhat different from those of stainless steel and other metal surfaces immersed in well water, glass slides are considered to be acceptable model surfaces because of the similarities of their surface free energy characteristics to that of metals (Hallbeck and Pedersen 1987). The surface free energy of a surface influences bacterial attachment. In addition, slides are readily available, inexpensive, and can be directly examined microscopically, or sampled for chemical analysis and for cultural recovery of microorganisms. The author has since also used metal coupons in these collectors.

The Howsam and Tyrrel (1989) moncell device represents an alternative collector method. The moncell collects deposits inside a sand-filled chamber from water trickling through the sand, which is then subsampled and examined microscopically for analysis of the biofilm present. Such sampling can provide an excellent model of filter pack phenomena. The collectors chosen in any case will collect a biofilm sample typical of that existing in the near well bore environment only (McLaughlan et al., 1993; Tuhela et al., 1993), however, this biofouling is usually the one of most interest for well fouling.

Literature in Support of Closed Basin Biofouling Monitoring

The preceding discussion cites a selection of literature, some more useful and relevant than others. The following are recommended for the project "bookshelf" as a range of available literature that ably summarizes the state-of-practice and provide a framework for the biofouling maintenance monitoring we are recommending.

Smith, S.A., 1992. *Methods for Monitoring Iron and Manganese Biofouling in Water Wells*. American Water Works Association/AWWA Research Foundation, Denver, CO. This project, conducted with Laura Tuhela and Olli H. Tuovinen of The Ohio State University, was a field trial of available testing methods for use in early warning monitoring of biofouling parameters.

It also provides an extensive literature and practice review of these forms of biofouling in wells and methods of analysis through that time.

Field test sites were three differing municipal wellfields in Ohio: Ada (carbonate rock, moderate iron, sulfide-present), Wapakoneta (carbonate rock, high iron, low hydraulic conductivity), and Tate-Monroe Water Association, New Richmond wellfield (Ohio Valley alluvium, low iron and manganese).

Sampling was conducted for on-site monitoring of Fe (total and ferrous), total Mn, total sulfide, temperature, pH, Eh, and conductivity and microbiological analysis. Pumped sampling (time series) was conducted for inoculation into IRB-BART, SRB-BART and SLYM-BART tubes, and R2A, W-R and R2A-FAC/Mn plates (all described in the report). In-well and flowcell slide collectors were used to collect biofilm samples for light and electron microscopy and elemental and crystallographic analysis.

Perhaps currently most useful is the framework for recommended monitoring, which is still valid and the basis of monitoring practice recommended to the project (Sections 5-7). Note that this report is currently out of print, but can be obtained from AWWARF.

Cullimore, D.R., 1993. *Practical Ground Water Microbiology*, CRC Lewis Publishers, Boca Raton, FL. This interesting book provides the original theory and handbook of practice for use of BART in biofouling monitoring. Practice in analysis has evolved significantly since 1993, although the theory and background outlined here are generally vindicated. Updates of procedures, including selection of tests, interpretation and quality control may be found on the Droycon Bioconcepts web site at URL http://www.dbi.sk.ca/droycon/barts.html and a new edition: *Practical Handbook of Bacterial Identification* (1999) is now available from the publisher.

Gariboglio, M.A., and Smith, S.A.,1993. *Corrosión e encrustación microbiológica en sistemas de captación y conducción de agua - Aspectos teóricos y aplicados*, Consejo Federal de Inversiones, San Martin, C.F., Argentina. As a matter of note, this work summarizes Argentine practice, which was developed under difficult economic and social conditions at the time, with a contribution by this report's author in the form of discussion on well design and maintenance aspects and practice in North America. The MAG test method, which is a methodology parallel to BART, was developed independently by Miguel Gariboglio and colleagues. It stands as the only known work on well maintenance in Spanish.

Howsam, P., B. Misstears and C. Jones. 1995. *Monitoring, maintenance and rehabilitation of water supply boreholes*. Report 137, Construction Industry Research and Information Association, London, U.K. This work by the U.K. group conducting work in this field, centered around Peter Howsam, again illustrates the international nature of these problems and solutions. Howsam previously had chaired and edited proceedings for 1990 conferences in the topic area (with papers from these works cited in the following) that include work from all the continents except Antarctica. This work is a concise, comprehensive manual of maintenance practice for water supply wells aimed at the water plant operator, but assuming familiarity with the testing methods recommended. It is better organized to dictate a maintenance plan than Borch et al. (1993) but is not as encyclopedic. Policy and economic aspects are summarized (this group has done the most complete economic analysis of well maintenance and rehabilitation in modern times). As in our recommendations to the project, Howsam et al. take a comprehensive view of monitoring, with biological, mechanical, physico-chemical and hydrologic factors all included.

McLaughlan, R. 1996. *Water Well Deterioration, Diagnosis and Control*. Technology Transfer Publication 1/96, National Centre for Groundwater Management, University of Technology, Sydney, Australia. This work provides an Australian perspective, and again illustrates the more or less universal nature of these problems. McLaughlan provides another highly useful summary of causes and diagnosis and control methods. These latter are very brief and include methods that are relative exotic for routine monitoring, but helpful at various points (for example, here early on when we are defining the nature of the clogs). A useful adjunct is the McLaughlan, Knight and Steutz (1993) publication cited, which includes details of the research behind McLaughlan's technology transfer publication.

Upcoming References

An update of Cullimore's 1993 text, Cullimore (1999) is now on the market but not yet evaluated by the author. Later in 2000, it is expected that Engineering and Design: Operation and Maintenance of Extraction and Injection Wells at HTRW Sites, EP 1110-1-27, will be available from the U.S. Army Corps of Engineers (it will be posted for download from the USACE web site). The schedule of availability will depend on the pace of USACE policy and format review. This document, although oriented toward pumping and injection wells at hazardous, toxic and radioactive waste sites, has many parallels to the problems in the Closed Basin.

Further Work

This is a first effort in support of research to identify methods for the analysis of biofouling. It is expected that Project ER99.40, Analysis and Control of Biofouling in Wells, Drains and Dams, will continue to gather information on analytical methods in years 2000-2001 and beyond.

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5. Recommended Monitoring Program for Evaluating the Long-Term Effectiveness of Closed Basin Salvage Wells Rehabilitated in 1998 and 1999

Purpose

It is an interest of the project to conduct monitoring of wells rehabilitated during methods tests in 1998 and 1999 (as described in Sections 2 and 3) to permit evaluation of short- and long-term responses to well rehabilitation in this select population of wells, with the intent to expand to a general well maintenance monitoring program.

Affected Wells

This monitoring recommendation is provided for

(1) Five wells rehabilitated in 1998 under contract # 98CS 8100 26, let to Laguna Construction Company, Albuquerque, NM. The salvage wells involved are SW-79, SW-82, SW-91, SW-100 (all Stage 3 wells), and SW-150 (Stage 5). The rehabilitation efforts of this project and their results are described in Laguna Construction Company, Inc. (1999) and supporting documentation, which were reviewed by the author (Section 2).

(2) Three Stage 3-4 wells rehabilitated in 1999 using a Blended Chemical Heat Treatment (BCHT) procedure, provided under contract let to URS Greiner Woodward Clyde Federal Services, with field services provided by ARCC, Inc., Daytona Beach, FL. The rehabilitation efforts of this project are described in Section 3 and notes supplied in the Appendix to this report.

These wells have experienced varied but significant decline patterns and appear to be experiencing clogging at least partially influenced by biofouling factors. The nature of the presumed well deterioration causes were summarized in Section 1. The SOW for well rehabilitation under Laguna's contract assumed that biofouling was a significant factor, causing a localized decline in hydraulic conductivity around the affected wells. Decline had apparently resumed in these wells by April 1999, when this section was first drafted.

Monitoring Scope and Purpose

Maintenance monitoring is one aspect of well problem prevention, maintenance and rehabilitation that is employed to provide early detection of deterioration of wells. The ideal is to detect deteriorating effects in time to prevent problems, allow the easiest possible treatment, or to schedule rehabilitation as needed in the most expeditious manner.

Monitoring rehabilitated well performance is addressed in a significant body of literature (e.g., Helweg, Scott and Scalmanini, 1983; Smith, 1992 and 1995; and Howsam, Misstears and Jones, 1995). The Helweg et al. work emphasized the value of well hydrologic testing. Smith (1992) provided a framework for biofouling and physico-chemical monitoring to detect symptoms of biofouling-related decline, while the latter two works provide an integrated strategy of maintenance monitoring to detect both performance decline and indicators of likely causes.

Due to the analytical history and symptoms expressed in these wells, the proposed monitoring will involve monitoring for both biofouling indicators and change in performance.

- In many cases, hydraulic symptoms of well deterioration may not be apparent until well biofouling is significantly reestablished. Water quality indicators of deterioration tend to be detectable before performance decline.

- Water quality and performance monitoring data are compared over time to establish trends in decline if any. The pattern of change, rather than absolute levels, are analyzed for water quality (biological or physico-chemical). Hydrologic parameters are also watched for trends.

Parameters useful in well maintenance monitoring

Hydraulic testing:	Flow and drawdown for specific capacity and (using step tests) change in formation and well loss and well hydraulic efficiency.
	Total amount of pumping time and quantity pumped per year.
	Periodic step-tests to analyze for changes in well, aquifer and pump efficiency (changes in aquifer and well loss components).
	Power consumption for pump efficiency.
Physicochemical parameters (for changes due to deterioration):	Total and ferric iron, and total manganese (Mn speciation patterns would also be useful in this case). Redox-sensitive metals readily taken up and modified by biofilms.
	Important anions as identified: e.g., sulfides, sulfates, carbonates and bicarbonates, organic C & CH_4 (potential indicators of biogenic changes).
	pH, conductivity, and redox potential (Eh) where possible (instrument readings may be replaced by checking ratios of Fe (total) to Fe^{2+} (soluble)). (All sensitive to biogenic changes).
	Turbidity or total suspended solids calculation of product water.
Microbial:	Total Fe/Mn-related bacteria (IRB), sulfur-reducing bacteria (SRB), slime-forming and other microbial types of maintenance concern as indicated.
Visual/physical:	Pump and other equipment inspection for deterioration.
	Borehole TV for casing and screen deterioration.

Pumping Tests: Purpose and Description

Reliable, valid tests are critical to well assessment and management. Such assessment and management are enhanced by a history of valid well data over time, back to installation if possible (which exists in the CBD database). Valid results depend on reliable, valid and reproducible test design, performance, reporting and interpretation.

Data collection

(1) Accurate discharge flow data are needed for any pumping test or long-term monitoring (see Section 3 discussion of case in point). Devices suitable for pumping tests include:

- Orifice weirs: Driscoll (1986) provides a detailed description of the necessary elements of the construction and use of an orifice weir. Orifice weirs are durable, accurate tools for wellhead tests and for calibration of mechanical flow meters.
- Mechanical flow meters may also be used. These that are installed in the SW discharge lines and used for long-term flow monitoring should be bench-calibrated for accuracy.

- Sonic-based flow meters available that are accurate and well adapted to this application.

(2) Equally important are time and water level measurements throughout the test or long-term monitoring:

- Existing SW water level transducers must be evaluated for reliable accuracy (as is currently done informally through review of database information for anomalies).
- Electric water level probes taking levels through stilling tubes provide a reliable and accurate means of manual water level measurement during tests.

(3) Water quality data: During tests, time-series water quality monitoring is recommended to detect trends, if any, due to progressive withdrawal of water during pumping.

Step-drawdown tests

Step-drawdown tests are probably the most valuable hydraulic testing tool available for assessing well performance in the context of maintenance and rehabilitation (Borch et al., 1993). When properly conducted and analyzed, they provide data on specific capacity (Q/s), and well and aquifer losses. Additionally, from the analysis, one can estimate well efficiency, and drawdown and specific capacity at a given discharge rate. Kruseman and de Ridder (1994) and Helweg et al. (1983) provide descriptions of these methods and their theory. The utility of data derived from the step-drawdown test is in the ability to:

- Determine characteristics about both the well and the aquifer simultaneously (aquifer and well loss and water quality) in addition to Q/s from one brief test.
- Extrapolate or interpolate the performance of the well at various discharge rates, using measured data points as a reference.
- Determine the operating characteristics of the well pump used.

Specifically designed and performed step tests (four flowing steps plus a shut-in step to complete a pump-performance curve) are recommended to replace the specific capacity test method documented in Laguna Construction Company Inc. (1999) during a one-year intensive evaluation period. The reason is that the step test can provide the additional well and aquifer loss and pump efficiency information and the potential for extrapolations to pick more appropriate pumping rates that minimize well losses.

For step-test data to be useful in calculating well, pump, and aquifer performance parameters:

- Data must be accurately gathered, with data collected at standard intervals of decreasing frequency as recommended (Helweg et al., 1983; Driscoll, 1986).
- Each step must be of a sufficient length of time for either the water level decline to stabilize or the decline trend to be established on a semi-log plot of drawdown vs. time (but does not have to be long, typically 30 to at most 100 min.).
- The effects of interference (such as other wells turning on and off) must be factored into the analysis. This is not expected to be an issue with the salvage wells.

To accurately determine Q/s for a well, accurate static water level, pumping water level and discharge rate data are needed. It is also useful to correct for changes in regional static water levels (if any), although step test analysis is relatively insensitive to these influences. For pump evaluation, pressure measurement at the pump discharge is needed.

Well Construction and Development History

Valid and complete development information is necessary to assess results and to provide benchmarks for future development efforts. This information is available in CBD records and computerized databases, however, accuracy has to be verified on a case-by-case basis.

Information on the redevelopment procedures used and their results, such as provided in Laguna Construction Company Inc. (1999) and Sections 2 and 3 (and attached note material) provides a basis for future analysis, especially
(1) Pumping test specific capacity and other hydrologic analytical results.

(2) Descriptions of material drawn into well:

- Amount and type of sediment material to determine its origin (need to know if it is aquifer or well pack).
- Biological results, such as the December 1998 Sangre de Cristo Laboratory results after well cleaning, which can be compared to data taken before and later.

Recommended Data Collection Intervals

The following are recommended data collection and analysis intervals for the eight wells in order to establish trends of deterioration after rehabilitation over one year.

Physical inspection	Borehole color video	One year after treatment to observe any changes.
	Surface facility inspection	Quarterly
	Examination of pulled components	As pumps may be pulled for service, and at the time of the video survey.
Hydraulic performance	Well discharge (flow rate and pressure)	As currently collected automatically.
	Drawdown	As currently collected automatically.
	Conduct graphical analysis	Monthly for automatically collected data.
	Specific capacity test (well hydraulic performance).	Quarterly for one year and then annually.
	Pump performance: Conduct 5-step “pump” test, compare to “nominal” data.	As a component of above scheduled step tests.
Electrical (power)	System and motor V, A, ohms and phase balance.	Weekly, Recommend installation of automated current monitors with alarms.
Physicochemistry	Inorganic parameters: pH, Eh, TDS, alkalinity, Fe and Mn (Fe speciated).	During step tests and quarterly using project on-site instruments (calibrated) or routine monitoring (laboratory).
	Turbidity (adds colloidal)	In-line monitors (continuous)
Biofouling Microbial Component	BART/cultural analyses: Wide suite (IRB, SRB, slime-forming and nitrogen manipulators (NO and DN)	Quarterly until patterns develop then drop all but the most indicative. Calibrate BART to laboratory option.

	Biofilm flow cell for microscopy	Annually on selected wells to monitor changes in biofilm composition.

Notes: This is a relatively intense monitoring program for eight wells under close scrutiny. However, based on the rate of decline in these wells, a one year intense period of monitoring is expected to provide a decline trend. By the time this final report is completed, the opportunity to conduct a rigorous one-year test (a recommendation made in mid-1999) immediately after the 1998 and now 1999 treatments has passed. However, a one-year trend can still be established, as the trends would be expected to continue.

It is not expected that this level of monitoring will be necessary for the long term on these wells or system-wide. In particular, after the initial monitoring period, step tests can be reduced to an annual frequency, and then to a calculated well maintenance treatment interval, when that is established. Physico-chemical and biological parameters can be reduced to a few that are sensitive indicators of change in these wells. In general, all opportunities to automate maintenance monitoring will be explored due to the number of wells to be monitored system-wide.

Method and Equipment Recommendations

(1) Hydrologic measurement for pumping tests: With bypass out of the well control pits, a flexible hose of suitable size (at least 6 inch diameter for the 253 to 510 gpm flow rates reported by Laguna) can be extended to an orifice weir.

For the reported flow ranges, an orifice weir with a 6-inch-diameter barrel is recommended, with two orifice plate ranges needed. For the smaller-flow wells (e.g., SW-82, SW-91, and SW-150), a 3-inch orifice provides a good measurement range. For the higher-flow wells (e.g., SW-79 and SW-100), a 4.5-in or 4.75-in orifice would be better. A 6-inch gate or globe valve (the latter is preferred) should be located at the intake end of the orifice weir (but at least two feet back from the entrance of the 6-ft-long barrel).

Flow rates from the orifice weir (which if properly constructed are inherently accurate) can be used for calibration of the in-line flow meter.

If possible, drawdowns should be measured manually by drawdown probe to calibrate transducer water level measurements. Because of reported cascading (e.g., SW-150), drawdown tubes (3/4-in I.D. rigid plastic) should be installed, extending to the top of the pump. If there is firm confidence in capacity of the existing transducer-sensor water level system to be sensitive enough for step test measurement (stabilization defined as movement of less than 0.02 ft over three 5-min. intervals), then this is a labor-saving alternative, as one person can run the test.

For pump performance curve generation, pressure measurement at the pump discharge (generally at the wellhead) is needed.

(2) Physico-chemical water quality: Existing sampling and analytical methods available for water quality monitoring through the Alamosa Field Office laboratory are suitable. Conductivity, pH, Eh, and redox-sensitive parameters such as ferrous Fe and total sulfides are best analyzed at the wellhead using portable instrumentation. Eh is preferably measured in a flowing system (the ORP electrode inserted into a flowing stream).

(3) Biofouling indicators: Biological Activity Reaction Tests (BART, Droycon Bioconcepts, Regina, Saskatchewan) are a de facto standard method for defining microbial ecology and

biofouling parameters in aquatic systems, and well-suited for ground water systems (Smith, 1996).

The CBD and Laguna Construction Company have employed Sangre de Cristo Laboratory, Alamosa, CO to perform biological analyses of interest in monitoring biofouling. The methods used are as described in Section 4. The usefulness of this laboratory's analysis should be evaluated in relation to other methods in common use. If appropriate and cost-effective, this lab's services can remain a viable alternative to BART.

Flowcell collection of samples for microscopic examination and mineralogical analysis of deposits (Smith, 1992; Tuhela et al., 1993) is recommended as a one-time event early in the monitoring period. Analysis of the mineralogical component permits refinement of chemical selections and microscopic analysis is used to identify structurally distinct microflora such as filamentous "iron bacteria" and also degrees of mineral crystallization.

Performing Tests

(1) A round of step tests on the five "Laguna" wells should be conducted as soon as possible (note that this has not reportedly occurred in the year since this task report was first drafted), with the recommended monitoring started at that point.
(2) Testing of the BCHT-treated wells (Section 3) cleaned in 1999 should begin soon thereafter.

Transition to Routine Maintenance Monitoring

A consideration in planning this effort is how this experience will be incorporated into long-term maintenance efforts (see Sections 6 and 7). After the initial evaluation period (expected to be approximately one year), maintenance monitoring of those wells kept in service from this group will begin to be integrated into the planned system-wide maintenance monitoring plan. Monitoring a significant fraction of 170+ wells with the above-described protocol would be very labor- and time-consuming. This initial eight-well monitoring effort (including the BCHT wells) should be used to refine methods and to streamline the effort as described in Sections 8 and 10 to make it as labor-saving as possible while providing valid data.

An important consideration is training or refreshing Alamosa Field Office personnel in the recommended techniques, and assembling necessary instruments and equipment so that they can conduct this monitoring themselves. The recommended monitoring will be an integral part of Closed Basin-wide well maintenance efforts in the future. Training and shakedown of testing equipment and protocols should be conducted as soon as possible, preferably in 2000.

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6. Maintenance Plan: Unaffected Stage 1 and 2 Wells

Purpose

Deterioration of Closed Basin salvage wells apparently has multiple contributing factors. A notable feature of the history of salvage well operations in the Closed Basin Division is the good long-term performance of the Stage 1 and 2 wells. Especially in contrast to the Stage 3-4 wells (see Section 7), the Stage 1-2 wells show steady long-term peak flow trends without serious decline trends. Section 1 reviews the causes of well decline in the Closed Basin, citing several possible reasons for these differences in performance.

The basis for this plan description and outline is (1) data and analysis provided from the files and databases of the Alamosa Field Office (AFO) Closed Basin Division, (2) the comprehensive cause analysis report by Hernandez (1998), and (3) additional relevant references that contribute to background on subject.

Preventive Maintenance Practice for Wellfields: Management Philosophy

A preventive maintenance (PM) program for wells and systems of wells or wellfields is not fundamentally different from the PM of other assets such as water treatment plants (e.g., Jordan, 1990), buildings or vehicles. The AFO has an existing maintenance program for its assets with a defined maintenance department, which identified the performance decline problems. This is a crucial function in PM. The struggle for the Closed Basin Division (CBD) since problem identification has been how to effectively carry out wellfield PM to halt or reverse declines in individual well performance and overall water delivery to the Rio Grande.

Wellfield PM is established to limit or retard well deterioration as part of an overall project wellfield operations and maintenance (O&M) plan already in place. For a variety of reasons, wellfield PM is not widely practiced. Instead, typical practice (e.g., in the Closed Basin project to date) is for wells to be rehabilitated when serious performance decline is detected. PM as a practice in wellfield operations is contrasted with rehabilitation as follows:

(1) Rehabilitation is usually done first to correct problems that have developed in the past and have resulted in unacceptably low levels of performance in a well or well system (a feature of the Stage 3-5 maintenance plan, Section 7).

(2) PM includes as a crucial function maintenance monitoring for signs of deteriorating conditions and impacts on performance and treatment as necessary to halt deterioration before unacceptable performance decline occurs. Experience and research (e.g., Sutherland, Howsam and Morris, 1993 and 1996) show that PM based on maintenance monitoring is less costly and far less disruptive to budgets, operations and system performance than repeated emergency rehabilitation over typical well life (20 years+). The principles of PM in general and specifically for wellfields are well-established (e.g., Borch et al., 1993) and field demonstrated, and the techniques much easier to use now.

Goals

The "first-order" goal of the PM program is to minimize performance decline and disruption. The "second-order" goals of a wellfield PM program are to carry out the specific acts that are known to serve the primary goal. These acts should be a combination of:

- preventive design and material selection (e.g., see Section 9),
- regular monitoring of indicators of possible well deterioration (maintenance monitoring) to detect changes that signal the onset of well and water system deterioration, and
- preventive treatments to control well and downstream fouling in its early "light" stages.
- operational patterns to avoid aggravating deteriorating conditions.

Preventive design and material selection

These are decisions in design and installation that consciously acknowledge that well deterioration is a reality, and serve to counteract or delay the effects of the deteriorating condition. In general, recommendations are as provided in the report reviewing the planned new well design.

Maintenance monitoring

This is monitoring for specific indicators that say that deterioration is happening. The ideal is to detect deteriorating effects in time to prevent problems or allow the easiest possible treatment. Usually it starts with a “research” phase to find out what’s going on, then monitoring a few key parameters that change when wells start to deteriorate again. The maintenance monitoring plan for the five "Laguna" and three "BCHT" wells (Section 5) offers details on methods.

Preventive well treatment

Maintenance or preventive treatments (a form of corrective maintenance) are those applied "pro-actively", usually on a schedule, and frequently at low doses. It is a subjective difference, but a maintenance treatment is contrasted to rehabilitative treatments in the latter type of treatments (1) are applied after deterioration is evident and are more intense, (2) use more chemicals, (3) take more time, and (4) have a higher risk of failure. Many of the methods are the same, but are usually less intense in a preventive mode.

Operational practices

These are practices consciously made, assuming well deteriorating conditions are inevitable, to minimize impacts. One decision is a closed-circuit feedback: establishing a PM plan and implementing the systems and practices that make it effective. From there, wells are operated so that identified deteriorating impacts are minimized. To make use of monitoring information and to implement PM measures such as treatment over time:

(1) A maintenance system must have organized and accessible records.
(2) Information collection should start with the project design phase and continue throughout the working life of the extraction and injection system.
(3) Records must be regularly reviewed by qualified personnel.

For example (and perhaps incidentally to PM), the CBD has a detailed automatic well data acquisition, recording and display system, which greatly facilitates well problem troubleshooting (See Section 8).

Maintenance Monitoring Practices

Summary of testing regime features

The following is a general summary of useful information to collect about wells for troubleshooting and predicting problems. The list (also included in Section 5) illustrates the multidisciplinary nature of maintenance monitoring.

Parameters useful in well maintenance monitoring

Hydraulic testing:	Flow and drawdown for specific capacity.
	Total amount of pumping time and quantity pumped per year.
	Periodic step-tests for well and pump efficiency (well and aquifer loss).
Electromechanical testing:	Power and fuel consumption for pump efficiency.
Physico-chemical parameters (for changes due to deterioration):	pH, conductivity, and redox potential (Eh) where possible (instrument readings may be replaced by checking ratios of Fe (total) to Fe^{2+} (soluble)).
	Important anions as identified, including sulfides, sulfates, carbonates and bicarbonates.
	Total and ferric iron, and total manganese (and other metals as indicated).
	Turbidity or total suspended solids calculation of product water.
	Calculation of corrosion/encrustation potential using a consistent method.
Microbial:	Total Fe/Mn-related bacteria (IRB), sulfur-reducing bacteria (SRB), slime-forming and other microbial types of maintenance concern as indicated.
Visual/physical:	Pump and other equipment inspection for deterioration.
	Borehole TV for casing and screen deterioration.

A primary objective of establishing a PM monitoring program is that it has to be cost-effective:

- "Effective" is defined as being capable of identifying intensifying deteriorating conditions (e.g., biofouling growth) and performance decline early enough so that PM treatment is effective.
- "Cost-effective" is doing this in such a way that the practice is not burdensome on staff and budget above and beyond the value of conducting the PM monitoring. The monitoring activity has to meet the project's standard of being "worthwhile to do."

Because of the large number of wells, an overall maintenance monitoring recommendation is to maximize the effectiveness of the existing electronic data acquisition, recording and display system operated by the AFO/CBD, which is supplemented by manual water quality data collection. Manually collected data are also recorded in the computer database. Continuing to use and maximize this PM asset will tend to minimize labor-intensive monitoring activities (see Sections 7 and 8 also). This existing system has a long-term data history and permits charting of trends and comparisons of a wide variety of parameters, features already used by Hernandez (1998) and this project's analyses to date.

Among the simplest parameters to monitor and interpret from the existing data options are flow trends. Both peak and average flows are recorded in the CBD system. Peak flow rates recorded are a useful indicator of well capacity change, assuming drawdown is constant at the cutoff point and the flow meter is accurate. The following "triage" uses flow trends as a basis for further review.

"Triage" Stage 1 and 2 Wells

One PM practice for wellfields without unlimited resources is to focus intense activities on key or problem wells, while monitoring other wells at a less intense level. In contrast to the maintenance recommendations for Stages 3-5 (Section 7), "triage" in Stages 1 and 2 should not need to involve abandonment of pumping wells in the near future. Based on a review of existing records, trends are relatively steady and all wells that produce water suitable for the project can continue to be used. The following are wells of some specific interest:

Stage 1-2 Well Commentary
Basis: Pumping charts provided in 1998, supplemented, and Hernandez (1988) report charts.

Wells of note in Stages 1 and 2	Flow features of interest	Recommendations
SW08, SW09	Increased flow rates, with decline trend possibly starting.	Reduce to 0.4 ft^3/sec, test and clean.
SW10	Showing decline trend at higher rate.	Reduce to 0.3 ft^3/sec, test and clean.
SW13	Showing decline trend at higher rate.	Reduce to 0.4 ft^3/sec, test and clean.
SW14	Increased flow rates.	Watch the peak flow trend at the higher rate.
SW16	Increased flow rates.	Watch the peak flow trend at the higher rate
SW19	Increased flow rates, with decline trend possibly starting.	Watch the peak flow trend for further decline.
SW16	Increased flow rates.	Watch the peak flow trend at the higher rate
SW21	Appears to have a dramatically increased peak flow trend that bears watching.	Watch the peak flow trend at the higher rate
SW32	Increased flow rates, with decline trend possibly starting.	Watch the peak flow trend: continued decline?
SW47	Increased flow rates.	Watch the peak flow trend at the higher rate
SW50	Appears to have a dramatically increased peak flow trend that bears watching.	Watch the peak flow trend at the higher rate
SW53 and 54	Appears to have a dramatically increased peak flow trend that bears watching.	Watch the peak flow trend at the higher rate, as there is a decline trend starting
SW58	Appears to have a serious decline trend in the peak flow rate - bears watching.	Watch the peak flow trend at the higher rate. Test and clean.
SW61	Appears to have a dramatically	Watch the peak flow

	increased peak flow trend that bears watching.	trend at the higher rate in light of an erratic average flow trend.

These wells should be specifically targeted for more intense monitoring (recommendations following). In addition, it is useful to know the characteristics of the "successful" wells also. The following Stage 1-2 wells are recommended for more intense monitoring because they represent apparently unaffected wells (to date): SW-17, SW-41 and SW-57.

These wells offer a cross section of conditions: SW-17 (Stage 1) has a relatively good sandy aquifer material profile and very low TDS. SW-41 (Stage 2) is shallower and more finely interbedded, with moderate TDS. SW-57 is somewhat similar to SW-41 but deeper.
Other wells should be monitored for flow, discharge pressure, pumping water level and water quality parameters as at present. Changes in production flow or drawdown greater than 10 % should be investigated further and action taken as needed. In addition: for all wells, the following inspections are recommended:

Physical inspection	Borehole color video	At pump service intervals. Concentrate on screen and other stress points.
	Surface facility inspection	Quarterly
	Examination of pulled components	As needed. Wells should be equipped for easy pulling if at all possible.
Electrical (power)	kilowatt-hour (kWh) usage, Ohms (Ω), voltage (V), amperage (A) and phase (ϕ) balance.	Continuously with alarms for out-of-specification conditions.
Physicochemistry		As currently monitored.

More intensive monitoring of picked wells

The following hydraulic, physical-chemical and biological testing is recommended for the wells indicated (in addition to routine water level and flow and physical-chemistry parameters now monitored):

Hydraulic performance	Conduct graphical analysis of data to look for trends	Quarterly.
	Specific capacity test (well hydraulic performance)(1).	Quarterly for one year, then annually or at service.
	Pump performance: Conduct 5-step "pump" test of pumps, compare to "nominal" data	One benchmark test for each well, then at least annually (Q/s and pump test can be a single operation).
Physical-chemical	Suspended particulate matter (sand, silt, clay)	Manually at well testing (as above), then annually or at service events.
	Turbidity (adds colloidal)	In-line monitors (continuous)
Biofouling microbial component	IRB(2), MPB, SRB, slime-formers	Quarterly until patterns develop then pick the most

		indicative to monitor quarterly.
	Biofilm flow cell for microscopy	Benchmark analysis of visible biofouling components.

(1) This should initially, then annually, be a step test. Automation of this procedure is technically feasible.
(2) Iron-related (precipitating) bacteria, manganese-precipitating bacteria, sulfur-reducing bacteria.

Maintenance Monitoring Methods for Extended Monitoring

Specific capacity and step tests

As mentioned in Section 5, reliable, valid pumping tests are critical to well assessment and management. Such assessment and management is enhanced by a history of valid well data over time, back to installation if possible. Valid results depend on their reliable, valid and reproducible test design, performance, reporting and interpretation.

Step-drawdown tests are probably the most valuable hydraulic testing tool available for assessing well performance in the context of maintenance and rehabilitation. When properly conducted and analyzed, they provide data on specific capacity (Q/s), and well and aquifer losses. Additionally, from the analysis, one can estimate well efficiency, and drawdown and specific capacity at a given discharge rate. Kruseman and de Ridder (1994) and Helweg et al. (1983) summarize and illustrate testing methods and analysis. The utility of data derived from the step-drawdown test is in the ability to:

- Determine characteristics about both the well and the aquifer simultaneously (aquifer and well loss).
- Extrapolate or interpolate the performance of the well at various discharge rates, using measured data points as a reference.
- Determine the operating characteristics of the well pump used.

If performed immediately after a well is constructed, the step test provides an estimate of the efficiency of the well and effectiveness of the well development phase of the well construction, and the baseline well and pump performance for comparison in the future. First checks of a well design's criteria or assumptions can also be made and adjusted as needed.

Note that well loss does not increase linearly to the discharge rate, therefore well efficiency and specific capacity are not constant and decline with increasing discharge rate. For step-test data to be useful in calculating well, pump, and aquifer performance parameters:

- Data must be accurately gathered, with data collected at standard intervals of decreasing frequency as recommended (Helweg et al., 1983; Driscoll, 1986).
- Each step must be of a sufficient length of time for either the water level decline to stabilize or the decline trend to be established on a semi-log plot of drawdown vs. time (but does not have to be long).
- The effects of interference (such as other wells turning on and off) and regional hydrological fluctuations (if any) must be factored into the analysis.

Static and pumping water levels can be affected by oscillations caused by the pump, cascading water, the water level probe becoming entangled in wiring and pump column, and operator error.

Pump, flow meter, pressure, electrical and water quality monitoring

Equipment should be accurate, reliable, and well matched to the data gathering needs and well operational environment:

- Water level data may be collected manually or the process automated.
- For relatively small numbers of wells (and as backup or supplement to automated methods on larger systems), electric water level probe and manual data entry.
- For larger numbers of wells where personnel time would be inordinately devoted to water level measurements: Instrumented airline or automated water level recording via transducers.

It is expected that the CBD will use the existing and generally reliable drawdown and flow measurement system, supplemented (and periodically calibrated) by electric water level sounders and portable flow-measuring methods such as orifice weirs (see Section 8). Wellheads should be modified to permit convenient manual water level measurement (see Section 7).

Material choices: The choice of materials to be used in devices for pumping and monitoring well performance is important to well system life and quality of service. Discussions of the material choice decision-making process are provided in numerous references (e.g., Powers, 1992; Borch et al., 1993; Smith, 1995; and McLaughlan, 1996).

Pressure measurement: Either manually read or digital read-out meters may be used. With both, plugging of sensor orifices is to be expected. To detect pressure changes in the conveyance system, pressure should be measured as near as possible to the wellhead, immediately downstream of the pump discharge check valve, and at strategic points in the piping system to detect changes in head loss. Measurements should be taken daily to weekly or automatically.

Electrical (power): Changes in pump motor total kilowatt-hour (kWh) and amperage (A) draw, circuit voltage (V) and ohms (Ω) are used to detect problems on the power side.

(a) Increases in kWh over time or A on start or run cycles indicate problems with motor windings or mechanical resistance such as sand in bearings. A drop in A indicates a loss of pressure resistance, such as if a hole has developed in the pump discharge pipe.

(b) Increases in circuit ohms indicates corrosion at connections. Fluctuations in V and Ω suggest wiring problems.

(c) Milli-Ω detections outside the circuit indicate ground faults.

(d) Voltage imbalance in three-phase (3-ϕ) systems cause excessive motor aging and poor performance, and should also be checked routinely.

(e) Total kilowatt-hour (kWh) use can be used to calculate changes in motor and system efficiency.

Water sampling: Strategically placed water sampling ports permit analysis of maintenance-related water quality parameters. These should be evaluated for their utility as maintenance monitoring sampling points. Where corrosion and biofouling are sampled directly using coupons (e.g., Smith, 1992; McLaughlan et al., 1993 and McLaughlan, 1996), provision must be made for attachment of the necessary sampling devices and discharge of flow-through fluids.

The usefulness of biofouling analysis depends on the sampling protocol (Cullimore, 1993; Smith, 1996). This is discussed in Section 4. In particular, if numbers such as plate counts are to be used as triggers for treatment, the sampling should be standardized.

(1) During an individual sampling event, the sampling times chosen should be standardized (Section 4, Cullimore, 1993; Smith, 1996) to the degree possible.

(2) Sampling should be conducted before any well treatment is anticipated, and not until two weeks of operation afterward to avoid the transient disruption of the treatment process.

Analyses: Physical-chemical analyses can proceed as at present, with graphical analysis conducted at least quarterly on the selected sample of wells in Stages 1 and 2. Biofouling analysis by heterotrophic culturing can be conducted using either BART methods or the services of Sangre de Cristo Laboratories (SDC Labs), as per Smith, 1992 and 1996. BART are highly useful, but SDC Labs has a history of detailed analysis for the CBD. As discussed with SDC Labs director Evelyn Vigil, we would recommend some changes in media formulation, but their essential procedure is sound. It may be useful to delegate sampling to SDC Labs as well to permit a single-source quality control on the biological testing.

Summary of Physico-Chemical Methods Relevant to Well Maintenance

Fe (total, Fe^{2+}/Fe^{3+}, Fe minerals and complexes):	Indications of clogging potential, presence of biofouling, Eh shifts. Fe transformations are the most common among redox-sensitive metals in the environment.
Mn (total, Mn^{4+}/Mn^{2+}, minerals and complexes):	Indications of clogging potential, presence of biofouling, Eh shifts. Less common but locally important in the Closed Basin.
S (total, $S^{2-}/S^{0}/SO_4^{2-}$, S minerals and complexes):	Indications of corrosion and clogging potential, presence of biofouling, Eh shifts.
Eh (redox potential):	Direct indication of probable metallic ion states, microbial activity. Usually bulk Eh, which is a composite of microenvironments.
pH:	Indication of acidity/basicity and likelihood of corrosion and/or mineral encrustation. Combined with Eh to determine likely metallic mineral states present.
Conductivity:	Indication of TDS content and a component of corrosivity assessment.
Major ions and methane:	Carbonate minerals, F, Ca, Mg, Na, Cl determine the types of encrusting minerals that may be present and are used in saturation indices. Methane is an identified factor in Closed Basin geochemistry.
Turbidity:	Indication of suspended particles content, suitable for assessment of relative changes indicating changes in particle pumping or biofouling.
Sand/silt content (v/v, w/v):	Indication of success of development/redevelopment, potential for abrasion and clogging.

The CBD data system provides the major metal and ion analyses and TDS. Adding capacity to spot-check redox potential and specific parameters and ratios of interest is recommended.

Records

Records should include the following, many available in CBD files:

(1) Physical locations and as-built descriptions of the wells and their equipment. The physical geographic location of well should include precise geographical references.

(2) As-built diagram of the well's construction, with any modifications over time.

(3) Lithologic log of the well as constructed. Well drilling and construction logs and any other logging data (caliper, gamma-gamma, etc.). Logs must be completely labeled with dates, depths, and borehole site identification. Include copies of interpretation reports in the file.

(4) Records of pumping tests and geophysical, borehole flow meter, etc. tests of the completed well over time.

(5) Pump performance data from pumping tests as applicable by date, include analysis and recommendations of pump performance reports. Note: It is most useful if these are graphically analyzed instead of just being recorded as data records, as seems to be the case for original step test data.

(6) Pumping and static water levels by date and time of day (as recorded). This should be distinguished out from "UWL" and be capable of being charted as PWL and SWL (Section 8).

(7) Dates of replacement of components, manufacturer and type of component, if known, and length of service, if known. Include itemized invoices with costs. Take photos or video tapes of deteriorated components for future reference, and include descriptions. Include copies of product owner operation and service literature. Document any contractor service personnel.

(8) Electrical, power and pump mechanical information.

(9) Water quality data from wellhead samples, plus biofilm collector results, listed by date. Keep track of labs and costs. Include reports analyzing water quality data.

(10) Electrical, power and pump mechanical (submittal literature, shop drawings, and nameplate) information.

(11) Details of well rehabilitation activities, including dates, diagnosis, if any, treatment methods, results, time involved, and costs.

(12) Color borehole TV survey videotapes: Take at any zero point, before and after well rehabilitation measures, and at service intervals. Tapes may be consolidated as summary tapes of important well features over the years. Label tapes by well identification and date and store properly in an accessible location.

Data Analysis

The data and other information mentioned are substantially collected by the CBD. A recognized concern is that large amounts of information is collected, but not utilized properly. More regular analysis is needed to view trends:

- Pumping flow rate/Drawdown (pumping water level - static water level) = specific capacity. Look for trends that cannot be explained by regional hydrologic events.
- Biofouling parameters: Changes over time.
- Inorganic water quality: Significant trends.

PM Treatment and Operational Changes in Stages 1 and 2

Other than the flow changes recommended, it will otherwise be useful to await the results of a year or more of maintenance monitoring results prior to implementing specific changes in operations or recommending treatment in Stages 1 and 2. PM treatments can proceed as recommended based on a review of recent well cleaning tests (Section 2 and 3) and planned work in 2000. No further action in this area is recommended until more information is gathered.

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Also files kindly supplied by Ella Mae Herrara and the AFO staff, whose work on accessing, organizing, interpreting and charting this vast and complex data set is gratefully acknowledged.

7. Maintenance Plan: Stage 3 to 5 Wells

Purpose

Deterioration of Closed Basin salvage wells apparently has multiple contributing factors. A notable feature of the history of salvage well operations in the Closed Basin Division is the very rapid and widespread loss of production in the Stage 3 and 4 wells in particular. Section 1 reviews the causes of well decline in the Closed Basin, citing several possible reasons for the causes and severity of these declines in performance. It is developing as a fact that maintaining well operations in this part of the Closed Basin is difficult due to multiple, interactive well deteriorating conditions as discussed in Section 1.

The basis for this plan description and outline is (1) data and analysis provided from the files and databases of the Alamosa Field Office (AFO) Closed Basin Division (CBD), (2) the comprehensive cause analysis report by Hernandez (1998), (3) onsite review of facilities and capabilities, conducted by the author in August 1999, and (4) additional relevant references that contribute to background on subject.

Preventive Maintenance Practice for Wellfields: Stage 3-5 Management Philosophy

Preventive maintenance (PM) philosophy is reviewed in Section 6 for maintenance of the Stage 1 and 2. The strategy for Stages 3 to 5 is different because wells have dropped in production in a dramatic fashion, and some performance recovery is necessary before a true state of maintenance can be established. Strategically, action will proceed as follows:

(1) Attempted rehabilitation of selected wells is planned as the first step. In fact, this has been ongoing as an operational response to low production for several years (see Section 2 and 3). The tests described and planned work are crucial in defining what will and will not work.

(2) Subject to funds being available: Replacement of wells that are no longer economical to operate and are not responding to rehabilitation sufficiently to make the effort worthwhile.

(3) Selection of wells that can be reasonably maintained by PM monitoring and treatment.

(4) Implementing a PM program on these wells, rehabilitated wells that are responding to treatment, and new wells.

Issues in the Process of "Stabilizing" Stages 3-5 Output

Defining well decline causes and reasons for limited well treatment response

As a result of the tests of the BCHT cleaning method, conducted in August and September 1999 (Section 3), it has become apparent that despite the apparent predominance of the biofouling component of clogging, that two other mechanisms are at least as important: (1) geochemical clogging and (2) clay smearing and swelling as a result of interaction with treatment chemicals and agitation.

It is likely that microbial biofilm development, especially in the highly oxidized and cascading zones around the top of screens, was the "nucleus" around which geochemical clogging developed. Such "biological cements" have been formed in models operated by the Canadian Ministry of Agriculture, Prairie Farm Rehabilitation Administration (PFRA) and its research partner, Droycon Bioconcepts Inc. The prevalence of fine sediment fractions could form a "biological concrete." These cemented, sediment-impacted clogs would resist dissolution and removal by chemical action.

Much of the clay in the Closed Basin apparently has a recent volcanic ash origin (Section 1). Montmorillonite (the active clay mineral in bentonite) is a typical volcanic clay with a high swelling potential. Swelling could conceivably close off thin sand seams around the pumping wells. Partial dissolution by chemicals could mobilize clay that could be mixed with sandy units during redevelopment. PFRA studies in progress show that certain chemical treatments cause clay swelling: particularly sodium-containing alkaline compounds such as liquid chlorine products, caustic soda, and alkaline wetting agents. Swelling occurs if left in contact with the clays for lengthy periods, (mostly beyond one day). These clay-associated restrictions in well production are largely permanent and irreversible.

Preventive design and operation

Information on the deteriorating mechanisms faced by wells in the Closed Basin is being used in preventive design for proposed new wells (see Section 9). Preventive design, as discussed in the Stages 1-2 PM plan and the review of the proposed new well design (Section 9), is still a matter of ongoing discussion in the project. However, the intent is to develop well designs that will slow performance deterioration and improve the effectiveness of future rehabilitation. This discussion includes existing wells that can be modified to permit easier treatment and monitoring, and also deciding what wells will not be cost-effective to treat and that should be replaced.

Preventive operation involves running wells to minimize deterioration, and making those adjustments necessary to avoid excessive oxidation, mineral deposition and local formation dewatering around wells. These are practices consciously made, assuming well deteriorating conditions are inevitable, to minimize impacts.

One such decision is a closed-circuit feedback process of establishing a PM plan and implementing the systems and practices that make it effective (this present effort and its intended outcomes). From there, wells are operated so that identified deteriorating impacts are minimized. The CBD has a detailed automatic well data acquisition, recording, and display system, which greatly facilitates well problem troubleshooting. Data charting and analysis needs are described in the Stages 1 and 2 maintenance plan (Section 6) and review of data acquisition needs (Section 8).

Maintenance monitoring

As discussed in Section 6, this is monitoring for specific indicators warning that deterioration is happening. The ideal is to detect deteriorating effects in time to prevent problems or allow the easiest possible treatment. Usually it starts with a “research” phase to define processes and benchmark performance, and then monitoring a few key parameters that change when wells start to deteriorate again.

To be effective, for a significant number of Stage 3-5 wells, maintenance monitoring will essentially be similar to that recommended for the eight 1998-1999 ("Laguna" and "BCHT") wells (Section 5). The intent is to have this monitoring be automated as much as possible.

Preventive well treatment

As discussed in the Stages 1-2 maintenance plan (Section 6), maintenance or preventive treatments (a form of corrective maintenance) are those applied "pro-actively", usually on a schedule, and frequently at low doses. It is a subjective difference, but a maintenance treatment is contrasted with rehabilitative treatments, in the latter type of treatments (1) are applied after deterioration is evident, (2) are more intense, using more chemicals, (3) take more time, and (4) have a higher risk of failure. Many of the methods are the same, but are usually less intense in chemicals, equipment and time in a preventive mode.

Maintenance Monitoring Practices

A cornerstone of PM for Stages 3-5 wells should be monitoring to detect performance deterioration and evidence of increasing clogging activity early enough to schedule PM treatment on a non-emergency timetable under normal contract service procedures of the AFO/CBD.

Summary of testing regime features

A general summary of useful information to collect about wells for troubleshooting and predicting problems is provided in the Sections 5 and 6. As discussed in Section 6, a primary objective of establishing a PM monitoring program is that it has to be cost-effective. This becomes more significant with the large number of Stages 3-5 wells:

- "Effective" is defined as being capable of identifying intensifying deteriorating conditions (e.g., biofouling growth) and performance decline early enough so that a scheduled PM treatment is effective.
- "Cost-effective" is doing this in such a way that the practice is not burdensome on staff and budget above and beyond the value of conducting the PM monitoring. The monitoring activity has to meet the project's standard of being "worthwhile to do."

As with Stages 1-2, because of the large number of wells, an overall maintenance monitoring recommendation is to maximize the effectiveness of the existing electronic data acquisition, recording and display system operated by the AFO/CBD, which is supplemented by manual water quality data collection. Manually collected data are also recorded in the computer database. Continuing to use and maximize this PM asset will tend to minimize labor-intensive monitoring activities. This existing system has a long-term data history and permits easy charting of trends and comparisons of a wide variety of parameters, features already used by Hernandez (1998) and this project's analyses to date.

Maintenance Monitoring Selection

Scheduling for PM will depend on regular maintenance monitoring to detect performance deterioration trends. The "Laguna" and "BCHT" wells, the new SW-75 well, and selected other wells would be specifically targeted for more intense monitoring (recommendations following). Wells selected should offer a cross section of conditions in depth, position, formation material, and problems. Testing over time would finally provide a systematic picture of the biogeochemistry of Closed Basin well problems and how they evolve over time. Other wells should be monitored for flow, discharge pressure, pumping water level and water quality parameters as at present.

Among the simplest parameters to monitor and interpret from the existing data options are flow trends, as currently used in strategy planning. Both peak and average flows, as well as UWL (unconfined water level) are recorded in the CBD system. Peak flow rates recorded are a useful indicator of well capacity change, assuming drawdown is constant at the cutoff point and the flow meter is accurate. UWL changes (if flow is constant) reflect clogging in the formation or screen. The following "triage" uses flow and drawdown trends as a basis for further review.

For all wells, changes in production flow or drawdown at the established production flow greater than 10 % should be investigated further and action taken as needed. Any greater loss may threaten substantial flow loss to the point where recovery is doubtful.

One problem, addressed in Section 8, is obtaining consistent and useful water level data to chart the highly useful and conventional well performance assessment value, specific capacity (flow (Q) per unit drawdown (s)), with Q/s conventionally expressed in the U.S. as gallons per minute (gpm) per foot of drawdown (gpm/ft).

In using Q/s values for assessing well condition, it is most useful to examine trends in Q/s over time. UWL recorded apparently reflect pumping water levels. Static water level values are irregularly recorded near salvage wells. Additionally, water level transducers at times record erroneous values or may be out of service for months, as was the case for SW-103 in 1998-1999, which made pretreatment performance assessment difficult. It will be imperative that pumping and static water levels be recorded be recorded regularly and reliably.

In addition: for all wells, the following monitoring or inspections are recommended:

Physical inspection	Borehole color video	At pump service intervals. Concentrate on screen and other stress points.
	Surface facility inspection	Quarterly
	Examination of pulled components	As needed. Wells should be equipped for easy pulling if at all possible.
Electrical (power)	kilowatt-hour (kWh) usage, Ohms (Ω), voltage (V), amperage (A) and phase (ϕ) balance.	Continuously with alarms for out-of-specification conditions.
Physicochemistry		As currently monitored.

More intensive monitoring of picked wells

The following hydraulic, physical-chemical and biological testing is recommended for the wells indicated (in addition to routine water level and flow and physical-chemistry parameters now monitored). Some wellhead and procedural changes will need to be made as described (following).

These are relatively ideal recommendations which have to contend with the reality of limited staff managing a large well system (in addition to other necessary tasks). The key to making this possible is selection of a representative group of wells for intensive monitoring and a realistic monitoring program for the other wells in the long term.

Monitoring recommendation for picked stage 3-5 wells

Hydraulic performance	Conduct graphical analysis of data to look for trends	Quarterly.
	Specific capacity test (well hydraulic performance)(1).	Quarterly for one year, then annually or at service.
	Pump performance: Conduct 5-step "pump" test of pumps, compare to "nominal" data	One benchmark test for each well, then at least annually (Q/s and pump test can be a single operation).
Physical-chemical	Suspended particulate matter (sand, silt, clay)	Manually at well testing (as above), then annually or at service events.
	Turbidity (adds colloidal)	In-line monitors (continuous)(2)
Biofouling microbial component	IRB(3), MPB, SRB, slime-formers	Quarterly until patterns develop then pick the most indicative to monitor quarterly.
	Biofilm flow cell for microscopy	Benchmark analysis of visible biofouling components.
	Chart well fouling index	Plot BART days of delay (dd) until reaction with Q/s. If dd shorten faster than Q/s declines, biofouling is the dominant problem. If dd remains relatively constant while Q/s declines, geochemistry is dominant.

(1) This should initially, then annually, be a step test. Automation of this procedure has been demonstrated technically feasible, but should be calibrated.
(2) Turbidometer sensors can be installed in-line, tapping downstream of the well flowmeter.
(3) Iron-related (precipitating), manganese-precipitating, slime-forming, and sulfur-reducing bacteria.

Selection of wells for monitoring

First, careful selection of wells can provide good information on processes and rates of deteriorating processes for the larger population of wells. Information from more intensive monitoring of this select group can be combined with patterns identified from limited monitoring of many wells to establish a feasible long-term maintenance monitoring program and refine it with experience.

A good population would consist of the 1998 Laguna-treated wells (SW-79, 82, 91, 100), the 1999 BCHT treated wells (SW-84, 99 and 103) (see Section 5), new SW-75 when completed and up to 12 other wells of interest, representing the various water quality conditions, stages, and wells treated by CBD staff. Some suggestions:

Low-TDS wells	SW-71, 86, 102, 112, 126,
Higher-TDS wells	SW-107, 136, 142, 160, 170
CBD treated wells	SW-95, 114, 144

Maintenance Monitoring Methods for Extended Monitoring

Specifics of methods and their purpose are provided in Sections 5 and 6. The CBD data system provides the capacity to monitor large numbers of wells for hydraulic parameters as well as major metal and ion analyses and TDS.

Adding capacity to spot-check redox potential (e.g., at the in-line turbidometer tap) and specific parameters and ratios of interest is recommended. This can be done on the wells selected for more intensive monitoring (as discussed above), with conclusions on geochemical mechanisms extrapolated to the rest of the well population with reasonable confidence.

As previously discussed, the step test permits detection of changes in screen-area (well loss) and near-aquifer (aquifer loss) hydraulic properties. This gives shape to recovering clogs, aiding in treatment design. Refining the recently demonstrated capacity to remotely step test wells (assuming that this procedure provides valid information) will provide a method to monitor a range of conditions in a well in a short test with minimal labor input.

It should be a feature of the PM monitoring to manually spot-check the accuracy of remotely transmitted data. The same conditions that clog and corrode wells also attack water-level transducers and flowmeters, causing slow drift before failure occurs. While AFO/CBD is now adept at spotting failure in these sensors, a better gauge of their drift may be useful. Once this is known, then a significant push to automating maintenance monitoring can proceed with confidence.

PM Treatment and Operational Changes

General

In contrast to recommendations for Stages 1-2 wells, rehabilitation and operational change will be an integral part of the immediate response to the crisis in Stages 3-5 wells. In some ways, PM for these wells will be simpler. While PM monitoring is a part of the process, Stage 3-5 PM monitoring goals should focus more on refining an essentially continuous PM treatment regime (moving in rotation from well to well). This is somewhat different than the early-warning monitoring focus in Stages 1-2, where wells currently provide adequate performance.

The logic of this process should proceed as follows:

(1) First, a firm triage will be conducted to determine the planned fate of wells (as discussed below for wells listed in the Appendix). Ideally, part of this should be an economic analysis based on the cost of repair and flow maintenance to keep specific wells open. This can be accomplished using present information on well cleaning costs and operational cost-benefit analyses such as those of Helweg et al. (1983). However, cost of pumping to the canal and a value for the benefit of water pumped into the Rio Grande are needed to conduct this analysis.

At present, the overarching issue is simply producing cubic feet of water, with cost-benefit as a lower priority. Here, the analysis can decide between rehabilitation/maintenance, inaction, and new construction in terms of millions of cubic feet per year added due to the action taken. For example, improving SW-103 Q/s from 9 gpm/ft to 13.5 gpm/ft adds potentially 2.7 million ft^3/year to production from this well. This is a quantifiable benefit.

Some wells will not respond well to rehabilitation, and thus rehabilitation money and effort would be wasted on them. The triage attempts to focus cleaning efforts on where they would do the most good.

(2) A realistic budgeting for PM of salvageable salvage wells should be established, with projections assuming one- and three-year intervals for cold PM treatment and maintenance monitoring. Also, budgeting assuming 10, 15, and 20-year replacements should be projected, with 20-year well lives the exception in this stage area.

The spreadsheet analyses of Sutherland et al. (1993) permits a projection of cost-benefits of maintenance monitoring if operating and repair costs are known. The experience with planned replacement SW-75 (Section 9) should show how conducting PM on a new well installed with the experience of the last 16 years will improve performance and reduce the cost of water transmitted to the Rio Grande.

(3) Eventually, an aggressive move to replacement should proceed if the economic analysis goes as we expect (costly annual treatments producing sometime meager results), with PM integral to the planning process for new wells. However, such strictly cost-benefit analysis has to consider how money is allocated. If money earmarked for new construction is unavailable or insufficient, rehabilitation is conducted as the alternative to loss of well production.

(4) A lower per-well yield more along the lines of < 200 gpm per well should be the basis for Closed Basin contributions, especially from Stages 3-5. Based on current preliminary analysis, Stage 3-5 wells should actually only be expected to produce an average of 163 gpm (0.36 cfs) when operated responsibly and maintained in optimal condition.

It is pointless to have treaty commitments for water supply that are not sustainable. Suggested yields are provided in the preliminary well-by-well analysis summarized in the Appendix to this Section (which should be refined with operational information over time). If more water is needed, more wells should be sited using valid hydrogeologic testing and analysis, constructed, and added to the system.

(5) PM treatments should begin immediately, with crews trained and devoted to the task. This training can proceed in time to have crews prepared before the end of good weather in the Valley during 2000, but 2001 is more realistic now. How this is conducted institutionally will depend on the AFO/CBD's preferences, budget and staff allocation possibilities.

"Triage" for Stages 3- 5 Wells

Treatment or abandonment and reconstruction?

One PM practice for wellfields without unlimited resources is to focus intense activities on key or problem wells, while monitoring other wells at a less intense level, and abandoning "hopeless" wells (ones that do not respond cost-effectively to appropriate treatment). In contrast to the maintenance recommendations for Stages 1 and 2 (Section 6), this triage will include a recommendation for abandonment of some wells in the near future.

The 1998 Laguna well cleaning episode (Section 2) has reinforced the uncertain and transient nature of well cleaning in this section of the Closed Basin. The "BCHT" cleaning in 1999 (Section 3) has provided experience with a cleaning method that will define what is possible in addressing the principal defined clogging mechanism: biofouling. It has also shed light on other problems (the geochemical cementing), and shown how combining methods (in this case, including Sonar-Jet) can improve results to some degree.

One lesson from these and other experiences in the Closed Basin is that results from even well-designed and (or) expensive treatments can be meager in wells that offer a low probability of return (in water pumped) on investment in rehabilitation effort. Careful selection of wells to be rehabilitated and maintained is important to optimizing water production improvement gained for dollars spent.

General triage recommendations

(1) It is recommended that intensive rehabilitation efforts be focused on wells currently producing in the range of 30 to 50 % of adjusted original specific capacity (Q/s). As per the recommendation in the Stages 1-2 maintenance plan, it is our opinion that an adjusted original Q/s (Q/s_a) be used as the benchmark.

Original Q/s values were probably inflated, as localized dewatering and compaction effects would not have been evident in the short-term original well acceptance tests. Based on a review of historical well performance, an arbitrary value of 60 % of tested original Q/s can be used to establish Q/s_a until a value can be determined in a more rigorous manner.

If rehabilitation returns a well producing at below 50 % of Q/s_a to greater than 50 % of Q/s_a, the well would be scheduled for PM chemical and redevelopment treatment annually unless output remains steady.

(2) Wells below 50 % of Q/s_a that do not respond to the rehabilitation methods determined to be effective would be scheduled for abandonment and replacement, with PM treatments conducted as needed to keep them as productive as possible until they are replaced.

The decision to rehabilitate or replace ideally should be based on a 10-year cost-of-water financial analysis. The "replacement" value would include an assumed three-year schedule for PM treatment and annual evaluation, in addition to construction, engineering and operational costs. However, if the USBR does not appropriate funding for new construction, maintenance treatments may have to continue on these wells indefinitely to maintain production goals.

(3) All wells sustaining Q/s_a above 50 %, rehabilitated wells returned to this level, and new wells (designed for sustainability per this project's recommendations) would be put on annual PM, with more intensive rehabilitation conducted on a case-by-case basis if it is judged that the work would be cost-effective in reducing decline or improving performance.

(4) Wells producing at < 30 % of original (adjusted capacity) should be scheduled for abandonment and replacement as appropriate without further rehabilitation investment. For example, very-low-producing low-TDS wells should be replaced.

Specific recommendations

Basis of recommendations: A preliminary analysis (list attached to this section) of 107 Stage 3-5 wells in the March 1999 printout supplied by AFO (74 pumping at that time) was used as the basis to evaluate the effects of (1) pumping at the top of the screen and (2) improving specific capacity.

- March 1999 cubic feet per second (cfs) values are used for flow unless a gpm value (e.g., for SW-84, 95, 99, and 103) is known.
- Pumping water levels (PWL) are estimated from recorded UWL, with assumed PWL = UWL and UWL adjusted to land surface. In a large number of cases, PWL had to be approximated, as UWL was absent or wrong (e.g., -178 ft in a 98-ft well). Approximation was made using either (1) a nearby well PWL or (2) the low-level cutoff elevation as the assumed PWL. The quality of these data should be improved for future analysis.
- Drawdown is estimated assuming an average static water level (SWL) of 13 feet below ground surface (3 ft is used where UWL indicate that the SWL is very shallow). This limited SWL information has to be filled in as part of the PM program.
- cfs x 449 = gpm is used to approximate gpm and Q/s approximated using these two approximated numbers. While this is a lot of approximation which should be reduced through testing, the Q/s values obtained are realistic for preliminary planning purposes.
- Using the depth to top of screen (ground elevation - screen elevation), an optimal Q in gpm from each well is calculated for a PWL at the top of screen at (1) the current approximated Q/s and (2) a realistic, achievable Q/s, for wells not slated for abandonment.
- A preliminary review of pump power requirements is also supplied. The adjusted horsepower assumes the new "optimal" gpm output and a generous 200 ft of system head.
- Flow as percent of original well capacity as reported by the AFO/CBD database is then used as the basis for triage. The reported percentage is adjusted to Q/s_a (reported percent/0.60) to judge against the 30- and 50-percent decision points.

The spreadsheet itself in Microsoft Excel format is provided in the report Appendix on disk. Information used is based on file information and limited testing, and should be adjusted using better information. The CBD can use and modify this spreadsheet using revised data and formulas provided to match new and better data. Current Q and accurate (measured) PWL can be inputted. Accurate Q, s, and Q/s values can be obtained from well testing (instead of the approximation formula used) and optimal Q based on history. Flow as percentage of Q/s_a can also be revised.

Summary of recommendations from this preliminary triage exercise: As analyzed with available data, the 74 wells would produce an average of 83.50 gpm at their file (rough approximate) Q/s or potentially 434 million ft^3/year (assuming 24-hr, 365-day operation) with PWL at top-of-screen elevation. At a realistic optimal Q/s, 65 wells would produce an average of 163 gpm or potentially 745 million ft^3/year (realistically, the amounts would be less due to down time, but proportional). Replacing poor wells at several good locations would add to this capacity.

- A number of wells that are below the 30 % of Q/s_a point can be abandoned, with power and resources saved that are currently allocated to their maintenance and operation.
- As mentioned above, the remaining 65 wells, with Q/s optimized by rehabilitation and maintenance, and with a PWL above the screen, can produce a significantly greater amount of water than impaired wells (potentially 745 million ft^3/year vs. 434 million ft^3/year) and more than the 74 wells operated in the present destructive manner (PWL well into the screen) (potentially 535 million ft^3/year). Some of this latter total is produced by wells pumping less than 100 gpm with motors of 15 hp or greater, which is highly inefficient.
- In all but a few cases, much smaller pump motors could be used, significantly reducing peak (start), total annual kWh usage, and replacement cost, and lengthening motor life.
- Several wells marked for abandonment (SW-96, 108, 115, 117, 121, 122, 146) should be reconstructed assuming any new well constructed in the formations at those locations would

produce valuable low-TDS water. At an average of 163 gpm, these would potentially add 80 million ft^3/year to the production total.

Well modifications for testing and treatment

A constant in planning for well maintenance is that the PM actions are not as regular, frequent, or effective as they should be if it is difficult to accomplish PM tasks. The current salvage well installation design has both positive and negative features in this regard:

(1) Positive:

- Individually equipped with automated sensors for flow and water level, and potentially for other parameters, with telemetry to the central data gathering center. It is not necessary to constantly travel to or disturb the well to obtain these essential measurements.
- Electrical controls are onsite and permit shutoff and operation from the surface.
- Pits are equipped for safe access and are not used for storage of other objects and supplies.
- Access around the well installations is generally good for heavy equipment.
- The pit access permits ready access to and removal of well pumps and installed equipment.

(2) Negative:

- The pit installation requires confined space access training and procedures to access and service well components.
- Access for manual testing of flow and water level is not available due to the bolt-down flange plate. Thus operations depend entirely on the installed flow meters and water level transducers, and calibration against manual measurements is difficult.
- Diversion for manual flow measurement or well treatment requires unbolting the flange and pulling up the pump. Thus, well treatment requires heavy equipment and crews.

The above-mentioned PM monitoring (especially for the wells marked for intensive monitoring) and treatment are best accomplished if there is a capacity for CBD maintenance crews to access the well casing and divert pumped water to the surface as needed without requiring a crane and without devoting the time required to open the top of the well casing and withdraw the pump. Reasons for access:

(1) Well treatment with chemicals and mechanical development and blow-off of spent chemicals and well clogging debris.
(2) Manual water level measurement to determine SWL and PWL and to calibrate transducer UWL measurements.
(3) Capacity to hook up orifice weirs or flowmeters to calibrate the in-line flowmeter.

Wellhead modification: A modification is suggested to permit access for PM water level measurements, treatment and development, and periodic manual flow testing. A hand sketch is supplied attached, which can be turned into a formal draft diagram:

(1) Wellhead tee arrangement for diversion and treatment:

- A tee arrangement should replace the current sweep ell. The tee would have the same spatial dimensions as the ell above the flange to the horizontal line hook-in so that it can bolt onto the discharge piping without further modification.
- The vertical extension of the tee can be finished with a butterfly valve and flange or a simple flat flange plate with gasket. Available 200-psi rated butterfly valves would provide a secure seal during normal operation. A plate would supply a secure seal.
- A standard extension (carried in service equipment, following) would extend up through the hatch to a convenient height for work on the surface. This can be made of pump column pipe or PVC to permit safe one-man hoisting and insertion.
- The extension would be equipped for (1) valved diversion and for attachment with quick disconnects to an orifice weir/flowmeter or treatment blow off and (2) valved recirculation of treatment chemicals in the well.

(2) The existing well-top flange plate can be modified to include a combination treatment injection and air development tube and manual water level measurement access. Use 1-inch 175-psi rated thick-wall rigid hose for the development hose in the well, and anchor it to the pump column. Extend into the sections of the screen most prone to clogging. The top terminus of the treatment-development tube should permit switching between a liquid hose quick-connect and a "Chicago" fitting for attaching compressor airline.

(3) A rigid plastic 3/4-in. line can be used for water level measurement. Extend to about one foot above the top of the pump bowls.

(4) If a wellhead sampling port for water sampling is not provided, install after the flowmeter.

It is recommended that wells be so equipped when scheduled for treatment and when pumps are serviced or replaced, starting as soon as possible.

Service equipment inventory: The existing service equipment inventory is appropriate, including an electric water level meter (M scope) and electrical measuring instruments and standard tools in an enclosed trailer. Recommended additions would include:

(1) Appropriate orifice weirs and exchangeable weir plates with leveling and blocking equipment or flowmeters of a size gauged to the well output.

(2) A box or flume weir for use in measuring flow during redevelopment.

(3) Standard water quality instrumentation or sample containers to return samples to the AFO laboratory. A pH meter should be part of the field equipment.

(4) Riser extension adapter as described.

(5) Modify the existing treatment tank trailer for easier mobility (road tires) and equip for mixing and feeding chemicals downhole.

(6) A mobile air compressor should be available. For development and airlift pumping up to about 200 gpm, a unit capable of about 185-CFM should be sufficient (~169 CFM can airlift 200 gpm).

(7) Add heater rig in the UAB configuration (PFRA/Droycon Bioconcepts): Conventional boiler (modified for travel, i.e., flexible insulation) feeding an insulated tank (500 gal), followed by an injection point from the chemical mixing trailer.

(8) Baffled receiving tank (approximately 16 ft X 4 ft X 2 ft deep) to facilitate neutralizing of chemicals as needed. This design can replace the large "frac" tanks.
(9) Necessary and spare fittings, chemicals and safety supplies.

A proposed PM treatment procedure

(1) Attach the described extension adapter (confined-space-trained person).

(2) Pre-treatment, test the well for specific capacity (either routinely or as part of the treatment procedure using a valid test pumping procedure).

(3) Attach the air hose fitting to the installed treatment tube and conduct a gentle air development of the well, raising and lowering the water rhythmically, then pumping to discharge to clear loose debris in the well.

(4) Attach chemical feed fitting.

(5) Mix relevant chemicals (see recommendation below), mix with hot water as indicated, and feed into the well and allow to sit and soak at least eight hours but no more than 24 hr (adjust this timing as experience dictates).

(6) Attach the recirculation hose to the extension adapter and mix in the well.

(7) Reattach the compressor, airlift develop and pump out developed-out debris and chemicals until clear. Use a gentle, rhythmic air pumping motion.

(8) Air pump until clear.

(9) Repeat steps as needed.

(10) Using the well pump, pump at various rates higher and lower than normal and turn on and off to induce additional clog sloughing. (This step can also be conducted periodically using the remote control to exercise and surge the well and pump.)

(11) Test pump for Q/s again to provide an "after" value.

(12) Repeat or expand treatment if indicated.

(13) Restore to the normal pumping configuration and return to service and make a record of the treatment event and its results.

Chemical choices

Chemical choices are currently undergoing evaluation. Based on the experience in treating SW-99 (Section 3) and inferences from the 1998 tests (Section 2), lengthy acid and surfactant exposure may cause clay mobility that either reduces Q/s or limits the benefits of other effects of the chemicals such as removing biomass and chemical encrustation. This is a useful working theory, but should be confirmed. It helps to explain the indifferent results of past treatments despite vigorous agitation and aggressive chemical use.

Heating is known to greatly improve the effects of chemicals and hot water itself may be used. One suggestion (from Brent Keevil of Droycon Bioconcepts) is to actually treat these wells with heated deionized water to attract encrustants into solution without inducing clay mobility. This novel recommendation has to be tested. The fluid would be expected to be very aggressive.

Based on the preliminary PFRA results that show clay swelling occurring after 1000 minutes or more of exposure (personnel communication), standard chemical choices can be used if in-well exposure is limited. On rehabilitated wells:

(1) Dose with one screen volume of a 0.1-percent solution of CB-4 (Calloway Chemicals, ARCC Inc.) buffered with HCl or sulfamic acid to pH 7.4. Develop in place, concentrating on the most impacted screen section.

(2) Pump in a 5 % acetic acid solution, permit to soak overnight. Develop out.

(3) Finish with a buffered CB-4 (0.01 %) rinse. Develop and pump clear.

(4) Evaluate and repeat as necessary.

If a more intensive biofilm removal is indicated, use a pH "flip-flop" keeping the limited exposure in mind:

(1) Dose with one screen volume of a 0.1-percent solution of CB-4 (Calloway Chemicals, ARCC Inc.) buffered with HCl or sulfamic acid to pH 7.4. Develop in place, concentrating on the most impacted screen section, and pump out debris and at least two casing volumes.

(2) Pump in a 5 % acetic acid solution, permit to soak overnight. Then develop out debris.

(3) Pump in 100 gallons of calcium hypochlorite solution (CaOCl premixed at 1000 mg/L in water) and develop. The start pH from residual acetic acid (about 4-4.5) results in hypochlorous acid, and an end pH as high as the 11 range provides a helpful pH reversal. Pump away until clear and pH drops to close to background.

(4) Finish with a buffered CB-4 (0.1 %) rinse. Develop and pump clear. Develop to a satisfactory end point to improvement in Q/s. Generally to a set goal or a point of diminishing returns.

(5) Evaluate and repeat as necessary.

Such treatments should be periodically reevaluated in light of experience and the availability of new information and products.

Personnel and Service Provision Issues

It was AFO manager Rich Demlo's assessment that the transition from Jim Mueller's "regime" to the "post-Mueller era" in 1999 went smoothly, with maintenance people "up to speed" in taking on responsibilities. However, it is a collective author-TSC assessment (Section 10) that a dedicated in-house well maintenance crew will be needed to really carry this effort forward. At least one dedicated crew of two people would help, but more would be better. The load on one two-person crew to monitor and service in the range of 60 Stage 3-5 wells that will require frequent attention will be considerable, with at most 30 weeks of good working weather.

In the long run, two crews of two should be working on Stage 3-5 wells, sharing resources and teaming with a similar Stage 1-2 crew as needed. It is likely that outside contractor support will be needed for about two years to catch up on the 90 wells currently with problems so that a transitions to routine PM is possible. Additionally, it is more cost-effective to utilize contractor support for heavy redevelopment and pump pulling, rather than having this specialized equipment in inventory. For service to be reliable, a maintenance contract with an outside contractor that guarantees service availability and a predictable level of business for the contractor is desirable. Further discussion is provided in Section 10.

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Also files kindly supplied by Ella Mae Herrara and the AFO staff, whose work on accessing, organizing, interpreting and charting this vast and complex data set is gratefully acknowledged. Also gratefully acknowledged is Brent Keevil, Droycon Bioconcepts and George Alford, ARCC Inc., for input on PM treatment blend and wellhead equipment modifications.

Section Attachments:

(1) Stage 3-5 well-by-well analysis and O & M recommendations
(2) Draft well modification recommendations

In Appendix: Supporting information

(1) September 21 to 24, 1999 tests of cleaned wells, conducted by CBD.

(2) Flow and UWL data supplied by the CBD.
(3) Charts of Flow and UWL trends supplied by CBD

Section Attachment: Stage 3-5 well-by-well analysis and O & M recommendations

Output from spreadsheet, provided as "3-5Triag.xls" (supplied on disk):

Bases and assumptions:

- March 1999 cubic feet per second (cfs) values are used for flow unless a gpm value (e.g., for SW-84, 95, 99, and 103) is known.
- Pumping water levels (PWL) are estimated from recorded UWL, with assumed PWL = UWL and UWL adjusted to land surface. In a large number of cases, PWL had to be approximated, as UWL was absent or wrong (e.g., -178 ft in a 98-ft well). Approximation was made using either (1) a nearby well PWL or (2) the low-level cutoff elevation as the assumed PWL. The quality of these data should be improved for future analysis.
- Drawdown is estimated assuming an average static water level of 13 feet below ground surface (3 ft is used where UWL indicate that the SWL is very shallow). This limited SWL information has to be filled in as part of the PM program.
- cfs x 449 is used to approximate gpm and Q/s approximated using these two approximated numbers. While this is a lot of approximation which should be reduced through testing, the Q/s values obtained are realistic for preliminary planning purposes.
- Using the depth to top of screen (ground elevation - screen elevation), an optimal Q in gpm from each well is calculated for a PWL at the top of screen at (1) the current approximated Q/s and (2) a realistic, achievable Q/s, for wells not slated for abandonment.
- A preliminary review of pump power requirements is also supplied. The adjusted horsepower assumes the new "optimal" gpm output and a generous 200 ft of system head.
- Flow as percent of original well capacity as reported by the AFO/CBD database is then used as the basis for triage. The reported percentage is adjusted to Q/s_a (reported percent/0.60) to judge against the 30- and 50-percent decision points.

Section Attachment: Draft well modification recommendations

(1) Wellhead tee arrangement for diversion and treatment:

- A tee arrangement should replace the current sweep ell. The tee would have the same spatial dimensions as the ell above the flange to the horizontal line hook-in so that it can bolt onto the discharge piping without further modification.
- The vertical extension of the tee can be finished with a butterfly valve and flange. Available 200-psi rated butterfly valves would provide a secure seal during normal operation.
- A standard extension (carried in service equipment, following) would extend up through the hatch to a convenient height for work on the surface. This can be made of pump column pipe or PVC to permit safe one-man hoisting and insertion.
- The extension would be equipped for (1) valved diversion and for attachment with quick disconnects to an orifice weir/flowmeter or treatment blow off and (2) valved recirculation of treatment chemicals in the well.

(2) The flange plate can be modified to include a combination treatment injection and air development tube and manual water level measurement access. Use 1-inch 175-psi rated thick-wall rigid hose for the development hose in the well, and anchor it to the pump column. Extend into the sections of the screen most prone to clogging. The top terminus of the treatment-development tube should permit switching between a liquid hose quick-connect and a "Chicago" fitting for attaching compressor airline.

(3) A rigid plastic 3/4-in. line can be used for water level measurement. Extend to about one foot above the top of the pump bowls.

(4) If a wellhead sampling port for water sampling is not provided, install after the flowmeter.

8. Evaluation of Current Closed Basin Division Monitoring Tools for Monitoring Deterioration of Closed Basin Salvage Wells

Purpose

Previous sections have (1) described the hydrogeologic and biogeochemical framework of the history of well deterioration in the Closed Basin (Section 1); (2) recommended monitoring schemes for use in well PM (Sections 5-7); and (3) reviewed microbiological monitoring methods suitable for biofouling monitoring of wells (Section 4). Each of these has discussed the Closed Basin Division's (CBD's) data gathering and analysis capabilities and parameters useful in PM monitoring. Sections 2 and 3 discussed the analysis of pumping tests and their effectiveness.

For completion of each of these tasks, data and other information have been requested from and supplied by the CBD and used in this project's analysis. The following is submitted for the purpose of reviewing the available monitoring and data management methods for the purpose of monitoring symptoms or cause indicators of performance deterioration in salvage wells as a part of well preventive maintenance (PM).

Available Data Collection and Evaluation Tools.

Parameters useful in well maintenance monitoring

As discussed in the PM plan recommendations (Sections 6 and 7), the following classes of parameters are recommended for well PM monitoring.

Hydraulic testing:	Flow and drawdown for specific capacity.
	Total amount of pumping time and quantity pumped per year.
	Periodic step-tests for well and pump efficiency (well and aquifer loss).
Electromechanical testing:	Power and fuel consumption for pump efficiency.
Physico-chemical parameters (for changes due to deterioration):	pH, conductivity, and redox potential (Eh) where possible (instrument readings may be replaced by checking ratios of Fe (total) to Fe^{2+} (soluble)).
	Important anions as identified, including sulfides, sulfates, carbonates and bicarbonates.
	Total & ferric iron, and total manganese (and other metals as needed).
	Turbidity or total suspended solids calculation of product water.
	Calculation of corrosion/encrustation potential using a consistent method.
Microbial:	Total Fe/Mn-related bacteria (IRB), sulfur-reducing bacteria (SRB), slime-forming and other microbial types of maintenance concern as indicated.
Visual/physical:	Pump and other equipment inspection for deterioration.
	Borehole TV for casing and screen deterioration.

AFO/CBD electronic data acquisition, recording and display system

The existing system operated by the AFO/CBD provides the capacity to electronically gather, record, and chart Unconfined Water Level (UWL), which is essentially the water elevation in individual wells, flow from wells in ft^3/sec (cfs), time of operation, and power used in kilowatt-hours (kWh). Data gathered from telemetry are supplemented by manual water quality data collection. Manually collected data are also recorded in the computer database. In addition, essential well dimensions (top elevation, screen top elevation, depth, length of screen, diameter of casing and screen) are also entered, based on engineering and contractor reports. From the Hernandez (1998) analysis, simplified geologic profiles tied to elevation became available in database form.

Benefits of the existing system:

1. A long-term data history that (if complete and accurate) permits studies of a range of trends.
2. The system permits charting of trends and comparisons of a very wide variety of parameters, features already used by Hernandez (1998) and this project's analyses to date.
3. The system enables at least simplified monitoring of a large number of wells with a minimum of labor-intensive monitoring activities.

System weaknesses: One weakness is inconsistent data quality. Both UWL transducers and flow meters are vulnerable to clogging by the same mechanisms that affected well screens and pumps (Section 1). In evaluating the histories of wells of interest during 1998 and 1999 well cleaning trials (Sections 2 and 3), absent and unreliable UWL data made valid assessments of changes in specific capacity (Q/s) difficult or professionally impossible.

This was an already-recognized condition and CBD was taking steps to improve the ability identify and correct UWL problems by our meeting in Alamosa in March 1999. The May "remote" Q/s test attempts discussed in Sections 3 and 6 was an opportunity to observe the benefit of recalibrated UWL data. When UWL were calibrated and tests run to sufficient length, Q/s values that were realistic and probably valid for qualitative comparisons were obtained. This test demonstrated the feasibility of regular monitoring of well Q/s, minimizing (but certainly not eliminating) time-consuming manual testing.

Physical-chemical monitoring: The CBD laboratory monitors a wide range of inorganic parameters, and histories provide sufficient information to analyze trends, for example, the proposed freshwater flush discussed in Section 1. Data available are sufficient to calculate simple corrosion-incrustation indices such as Ryznar or Langelier, for determining solubility equilibria using conventional methods, or entering into geochemical models such as PHREEQC (U.S. Geological Survey).

These data analyses permit an evaluation of likely clogging mechanisms active in addition to the much-discussed biofouling. Parameters recommended for PM monitoring are discussed in the PM monitoring plans (Sections 5, 6 and 7).

Biological monitoring: The range of biological monitoring methods suitable for CBD PM monitoring is discussed in Section 4. Historically in the Closed Basin, microbiological analysis of biofouling has been used mainly as a diagnostic tool for wells that have already experienced noticeable pumping, water quality, and other problems. Only in relatively recent times has monitoring for preventive maintenance been considered as a practical way to assess the (1) extent of biofouling, and (2) potential for future biofouling. Both analytical and sampling methods have been inadequate until very recently for the purpose of PM monitoring.

A discussion with Evelyn Vigil of Sangre de Cristo Laboratories (SDC Labs) of Alamosa in August 1999 provided insight into past testing. SDC Labs was contracted to conduct plate count analyses of various microflora types (iron-precipitating, manganese-precipitating, etc.) using cultural methods of Section 9240, *Standard Methods for the Examination of Water and Wastewater*.

(1) The laboratory had no control over the sampling procedure and there is no specific protocol for sample collection, handling and transport.

(2) The available testing procedure could not evaluate relative improvements resulting from cleaning.

(a) Samples were collected during the Laguna well cleaning (Section 2) while the work was under way and the biofouling highly disturbed and damaged.

(b) There was no time-series sampling and analysis to evaluate changes in biofouling presence over time.

It should be noted that this is the normal situation in water operations and not a peculiar shortcoming of the CBD and its operations.

(3) As discussed with Mrs. Vigil, current thinking in biofouling analysis is moving away from agar plate-based media and toward controlled broth media for more enrichment environments more likely to recover microorganisms present that are responsible for biofouling.

(4) Sampling methods and protocols are available that permit an evaluation of change over time in biofouling, and more reliable collection of samples.

Downhole video: The CBD has the very useful color downhole video device in its inventory. This tool permits direct observation of in-well deposition on screens and visible damage. For example, videos of SW-84 and SW-99 show visible clogging concentrated in the upper screen sections close to the pump setting points (Section 3) and clear screen in deeper sections.

Depth indications are important information in downhole video. It was not clear that the depths marked on the SW-84 and SW-99 videos were accurate, or to what benchmark the depths were measured against. For example, SW-84 top of screen depth is recorded as 41.6 ft below flange in records, but was at depth 34.7 in the video. The depth difference in SW-99's video may have been the difference between flange and surface elevation. Depth markers should be zeroed against a set, consistently chosen elevation.

Commentary is also good. Any information that the camera operator or expert commentator can provide is helpful to the viewer. On the technical level, the center-mounted mirror tends to provide a confusing image if the viewer is not accustomed to it.

Manual gathering of hydrologic and other relevant data: As discussed in the PM plans for Stages 1-2 and 3-5 (Sections 6 and 7), some manual gathering of information in addition to the telemetry data is necessary for calibration and other specific testing purposes. At present, manual flow testing at full pump capacity is typically confined to pump-servicing events, and the general operational plan relies on automatic gathering of hydrologic data.

However, some manual flow and drawdown testing is needed. Accuracy in both flow (Q) and drawdown (s) is important in calculating Q/s and near-well screen and aquifer parameters, as discussed in Sections 2 to 7.

The need to more accurately measure flow has been discussed within the CBD and TSC management and research group and in Sections 3 and 7.

(1) Analysis of flow testing of SW-84, -95, -99, and -103 in 1999 showed the inaccuracy of the flow meter used below approximately 250 gpm.

(2) Orifice weirs constructed for the "Airburst" test appeared to meet standard design criteria, however, they were either too small or too large for SW-99 pre-treatment testing, and flow charts were not available for them.

Recommendations

Using the electronic data system for routine PM monitoring

As discussed in Sections 6 and 7, use of the capacity to automatically gather and electronically chart data trends remains a crucially important tool in salvage well PM in the Closed Basin. For 170 wells, it is not feasible to manually monitor all of them.

Flow measurement: Among the simplest parameters to monitor and interpret from the existing data options are flow trends. Both peak and average flows are recorded in the CBD system. Peak flow rates recorded are a useful indicator of well capacity change, assuming drawdown is constant at the cutoff point and the flow meter is accurate.

Recommendation: Develop or refine a reliability history of the flowmeters in the inventory and watch for signs of decay in accuracy due to clogging effects. Calibration of typical meters during the "intensive" monitoring recommended for selected wells in the PM plans should assist in this effort.

Water level accuracy: Having accurate UWL values and histories without gaps permits long-term evaluation of Q/s trends, when UWL are combined with valid flow data.

Recommendations:

(1) Define static elevations in wells and calibrate transducer-read elevations to these zero points frequently.
(2) As the static elevations may vary seasonally or due to precipitation variations, it may be necessary to spot check static elevations manually to provide a valid calibration point.
(3) When transducer readings become unreliable, change the sensors as soon as possible.

Automating well testing: The "automatic" Q/s test appears to be a valid procedure, even if the "automatic step test" is less reliable, based on the May 1999 tests.

Recommendation: Assuming that UWL readings can be calibrated and valid static and pumping water levels (and flow) can be measured in this way, this procedure provides an economical way to monitor performance changes in a large number of wells, and the capacity to chart Q/s changes over time. This validity should be verified over a year (as soon as feasible) on all the wells selected for "intensive" monitoring (Sections 5-7).

Manual well hydrologic testing

The importance of valid pumping tests and how to conduct them were discussed in previous sections. Truly valid assessments of treatment results require valid pre- and post-treatment well

pumping tests. Flow meters or orifice weirs sized to the well output are needed, and valid step testing procedures followed. An apparatus modifying the wellhead to make such testing easier is described in the Stage 3-5 maintenance plan (Section 7). These procedures and their analysis are previously described and in several of the supplied references.
Recommendation: As discussed in the maintenance plan reports, a series of orifice weirs or suitable flow meters, sized to the range of flow capacities, should be a part of the CBD maintenance inventory for use in well cleaning pre- and post-testing and calibrating in-line flowmeters. Orifice weirs are simple and inherently accurate if constructed according to standard design (and leaks minimized). They do not drift as mechanical flow meters will, do not have vulnerable electronic components, and can be repaired locally if damaged. The authors can supply plans or ready-made orifice weirs and flow charts for them if necessary.

Using data in modifying triage decisions

With improved and ongoing data, the CBD should revisit the spreadsheet supplied with Section 7 and update the flow rates, static and pumping UWL, Q/s values (actual and potential), and add or subtract wells as needed.

Biological testing and calculating a well fouling index

SDC Labs as a service provider: If a facility is faced with the task of biological monitoring of a 170-well system, having a knowledgeable laboratory nearby is a major asset. It is the author's opinion that SDC Labs is qualified and should be contracted to provide long-term well biofouling testing services as part of the PM effort. It is recommended that SDC Labs incorporate current BART technology and methods in this effort, side-by-side with plate methods if SDC Labs at present has more confidence in these (and to provide a comparison to 1998 data). The author has supplied SDC Labs with information on improved analytical and sampling methods, and CBD should work with SDC Labs to establish a sampling protocol.

Well fouling index: A method that has been informally used for years has been given a name, "well fouling index" (WFI) by Droycon Bioconcepts. In this procedure, changes in BART reaction times (over time) are charted against historical Q/s values. In the Droycon procedure, if BART reaction times shorten faster than Q/s declines, the interpretation is that the clogging mechanism is primarily biological. If BART reaction times remain constant, the clogging mechanism is likely to be more geochemical or physical.

Recommendation: It would be highly useful to perform this analysis over a period of at least one year and probably several years.

Charting and Using GIS in Evaluating Data for PM

One problem in evaluating the information available for the Closed Basin salvage wells is that the existing body of information is almost overwhelming in size and complexity. Evaluation of the quality of the data and making intelligent judgments on processes and trends can be difficult.

One highly useful mechanism for making sense of such a huge and complex information set is to present it graphically. In addition to linear plots such as can be generated from spreadsheets, spatial mapping is also often highly illustrative. To date, we have not seen a fully developed example of collected and summarized information on the geographical and depth distribution of critical parameters such as Q/s, static UWL or clogging indicators (although Hernandez's work forms an example of such a work). We assume that this work has not been done.

Recommendation:

(1) On a digital base map in ArcView or equivalent, static and long-term pumping UWL should be plotted, along with UWL from nonpumping monitoring points. The exercise should be repeated periodically to chart changes over time. Comparisons can be made to original and other past conditions. The change from the original storage conditions to the current equilibrium should be apparent.

(2) The lithology and stratigraphy should likewise be plotted to provide a more systematic model of the distribution of productive and nonproductive (e.g., clay) units in the basin.

(3) In the same way, useful indicator parameters such as total organic carbon, TDS, and metals, and calibrations such as Ca-Mg saturation indices, can be plotted geographically, updating from older work (e.g., Emery et al., 1973 and Mayo and Webber, 1991). Such patterns can be used to make decisions on well usage and placement.

(4) A similar plotting of percent changes in WFI can provide a means of analyzing the relative importance of clogging mechanisms at various points in the Closed Basin.

(5) A numerical model of the Closed Basin unconfined section based on prior U.S. Geological Survey Work (e.g., Leonard and Watts, 1989) should be loaded and used regularly as a management tool. With this model, the effects of discrete changes such as dewatering at specific cells (representing individual salvage wells) can be tested experimentally to verify or modify hypotheses such as ours that the upper unit storage has been depleted. Long term pumping effects under varying climatic conditions can be modeled in "real time." Such models are a useful adjunct to the more well-specific information analysis available to the CBD and part of what the authors refer to as "total wellfield management" (TWM).

At the request of TSC, the authors are delivering a basic ArcView representation of the Closed Basin, with characterization of well performance and potentially influencing factors (flow regime, water quality, etc.) visually represented. The authors also have the capability to develop a full TWM approach and recommend that we be involved in further PM plan implementation until CBD can do so independently.

General Recommendations

(1) Valid and useful data and information are gathered by the existing CBD monitoring tools, however, calibration has to be more stringently conducted and data gaps reduced.

(2) The telemetry system is a powerful tool permitting low-cost gathering of data from many wells. The database and data analytical system permits very flexible analysis of a wide range of cross-referenced parameters.

(3) Manual gathering of flow and water level to spot-check and supplement telemetry-supplied data will be an important part of this calibration effort and in developing reliable Q/s histories for salvage wells. It is not especially difficult to gather important well data, but measurements must be as accurate as possible and testing conducted in a systematic manner using field-tested standard methods. Recommendations made in the PM plan reports should make this easier.

(4) Biological testing for routine PM monitoring is now effectively at the zero point, and should be systematically included in the monitoring effort. WFI calculation can help in future well rehabilitation planning.

(5) Systematic pre- and post-treatment testing should be conducted, recorded and charted to permit long-term evaluation of well cleaning efforts and the utility of rehabilitating specific wells as part of the PM triage function.

(6) Cost-benefit analysis would be a useful adjunct to other data gathering and analysis efforts and improve the CBD's ability to budget and win funding for enhanced PM efforts.

(7) Geographical plotting and modeling of various bodies of information will permit easier and more effective analysis of this large body of almost overwhelming information and permit easier and more effective predictive analysis. It will also provide a way to inform others, such as budget and policy decision-makers, about conditions and efforts in the Closed Basin wellfield.

The above refinement in data gathering, analysis and display should make both the specific PM effort, and the overall CBD management effort easier. Recommendations on the prioritization and cost-benefit analysis of these recommendations is provided in Section 10.

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9. Review of Plans and Specifications for the Rio Grande Water Conservation District 1998 Replacement Salvage Well SW-74 Project

Purpose

The purpose of this review is to evaluate the proposed general well design from the standpoint of how it would affect future well maintenance efforts and the expected well performance life expectancy in light of probable causes of salvage well performance deterioration (Section 1) and experience with rehabilitation (Sections 2 and 3) and plans for well maintenance (Sections 5-7).

This experience history with the current well design and construction (as reviewed in Section 1) should be a major factor in an improved design and has been discussed during new well design planning. Revisions of the original salvage well design discussed focused on avoiding the dewatered-screen condition and not exceeding the safe capacity of the Closed Basin aquifer units.

Design Comments (Preliminary Copy)

The Alamosa Field Office (AFO) provided a copy, dated October 1998, of "Plans, Specifications and Contract Documents for the Rio Grande Water Conservation District 1998 Replacement Salvage Well SW-74 Project," prepared by Davis Engineering Service, Inc., Alamosa, CO. This iteration of the plans is the basis for this review. Only technical specifications relative to the well design and construction itself are reviewed. Comments are provided section-by-section, keyed to the organization and pagination of that revision.

1.2 Test well drilling, test hole (p. 38): This is entirely appropriate assuming that this is a test well. A recommendation is to include gamma logging with possible electric logging to provide additional strata correlation. We recommend that the geophysical logging be part of the SOW and not optional. We recommend that the drilling procedure be more specifically described, with specifications for a drilling fluid program and bit selection and maintenance similar to the well construction specification. Mud rotary drilling should be conducted using a well-controlled low-solids, high-viscosity bentonite mixture, with phosphate "mud breakers" prohibited. Another technically feasible alternative for test drilling is cable tool methods, which provide very high quality samples in a reasonable time in alluvium to 120 ft. Specifications can be derived from NGWA (1998), Driscoll (1986) or ADITC (1997), or we can supply language.

1.3 Samples (p. 38): Assuming the drilling method is direct mud rotary, it is recommended that cuttings for sieve analysis be unwashed to avoid washout of natural clays and distortion of the sieve analysis. We recommend that the sampling method with alternatives be tightly specified. These will be crucial to optimal screen and filter pack design. Specifications can be derived from NGWA (1998), Driscoll (1986) or ADITC (1997), or we can supply language.

1.4 Test well completion (p. 39):

(1) PVC casing should be specified as "water well casing" and is usually designated in SDR sizes. SDR-21 would be appropriate. If this is to be a test well with casing withdrawn, a threaded-and coupled or spline-lock joint connection would be appropriate. If left as an observation well or as part of a well array (see following), joints can be cemented bell joints.

(2) Specification of this screen and filter pack is suitable for obtaining bids. We recommend that there be provision to modify the sizing based on formation particle sizes

encountered. Particularly in the 35- to 70-ft zone (interbedded clay and sand in the existing SW-74) there should be room for flexibility.

1.5 Well development (p. 39): “Disinfected” rather than “sterilized” is a realistic standard. “Sterilizing” is highly unlikely.

2.1 General (p. 40):

(1) The decision to make an offset pitless installation is an excellent choice. In fact, multiple wells could be sited this way at each installation.

(2) As previously discussed among AFO and USBR Technical Services Center and consultant personnel, an alternative to single, relatively large wells should be explored. That is, multiple (e.g., four) smaller-capacity wells rather than single, larger wells to provide the flows desired from any one location without overpumping the upper unconfined unit and inducing cascading flow. In this case, based on a cursory review of flow history, an installation design yield of 0.5 cfs (~224 gpm) is probably optimal.

This could be supplied by four, widely spaced 60-gpm pumps (four-inch diameter) installed in six or eight-inch I.D. casings (depending on instrumentation needs) with pipe-sized screen, rather than one 16-inch well casing with 14-inch screen.

Additionally, the upper and lower unconfined units can be screened separately in a well array, instead of spanning the section, as is the practice with the current salvage wells. In this way, the apparently more productive upper unit and the lower unit can be tapped without limiting construction to one large well with a depth limit of 70 ft as expected here.

2.3(a) Equipment and 2.4(o) Sequence of construction... (p. 41, 43): Again, here and elsewhere, “sterilizing” is an unrealistic standard, but having equipment demonstrated clean and disinfected is appropriate. Also, the well should be disinfected to State of Colorado standards for water supply wells.

2.5 (a) General (p. 43): For the smaller casing hole sizes, direct mud rotary or cable tool would be appropriate. No in-ground mud pits would be needed and better fluid control is possible.

2.5 (b) Drilling fluid (p. 43): Specify “bentonite only” for clay and be more specific about the fluid program (using NGWA, 1998 or other language sources). Also specify “no Revert” or other biodegradable or organic polymer muds. However, most drilling mud bentonite mixtures contain some polymer, which should be acceptable.

2.5 (d)(2) Drilling (p. 45): With direct rotary, enclosed mud pit tanks as recommended by drilling fluid suppliers are suitable and highly recommended to reduce contact with the microbially contaminated surface and to provide better fluid management (ADITC, 1997; Driscoll, 1986; NGWA, 1998).

2.6 (c) Pump chamber casing (p. 46): SDR-21 PVC water well casing of appropriate quality could be substituted without sacrificing installation quality, and for the long term, reducing corrosion potential relative to welded black-pipe steel casing. A cement grout of this depth and thickness would not cause casing distortion, particularly if filled with water during setting (NGWA, 1998).

2.10 (b)(2) Well screen assemblies (p. 51): Screen slot size should not be prejudged except for cost estimating purposes, but selected based on sieve analysis as provided for in para. 2.10(b)(1). Multiple slotting may be called for depending on the distribution of interbedded clays and sands. The optimal screen and filter pack efficiency will slow clogging impact.

2.10 (d) Installation (p. 52): Screen could be pipe-sized with cable tool or telescoping with rotary installation, permitting larger total open area.

2.11 (a) Filter pack and Table 2D (pp. 53, 54): Filter particle size should not be prejudged except for cost estimating purposes, but selected based on sieve analysis as provided for in para. 2.10(b)(1), matched to the screen, per standard practice (e.g., Driscoll, 1986; Roscoe Moss Company, 1992). Filter pack annular radius should be as small as practical for exclusion of fines.
2.11 (c) Filter pack placement (p. 54): We recommend installing with chlorinated water as outlined in NGWA (1998). The necessity for 2-inch grout pipes in a 70-ft installation should be reviewed.

2.12 Development (pp. 56, 57): The development procedure is excellent.

2.13 Sterilizing well (pp. 57, 58): Disinfection is the standard.

2.14 (a) Test pumping equipment (p. 58): An orifice weir is recommended for flow measurement. Alternatively, a two-chamber (2 m^3) flume with V- or square-notch weir of known dimensions. The inadequacy of well testing standard practices used in the Closed Basin project have been discussed at length in this report.

2.14 (b) Test pump (p. 58): The test pump should be pre-sized based on step testing of the test well specified, and the generator sized to the motor. “Overdriving” these wells is an issue in the deterioration of the current salvage wells (Section 7), and should be avoided.

2.14 (d) Discharge pipeline (p. 59): Total leakage from joints should not be more than 2 % of nominal pumping rate. For example, if a lower rate (such as 60 to 100 gpm as recommended) is being pumped, 2 gpm each from 10 joints in 500 ft would be 20 gpm and severely distort the test. In fact 20 gpm would distort a 200-gpm test.

2.14 (e) Water level observation pipe (p. 58): This could be rigid plastic such as CPVC (we assemble using threaded joints) and could be ¾-in (but no smaller). See Section 7.

2.15 Surging and testing: Again, excellent.

2.16 Records (p. 61): We recommend that field logs for drilling, construction and testing be specified and required to be kept and available for inspection at any time by the Engineer. Copies of these “raw” logs should then be kept on permanent record at the AFO.

Addition to item 2: Recommend adding final gamma log of the installation to pinpoint clay zones.

4.2 (a) Submersible pump: The specification notes that the pump will be sized to the well installation after testing. Moving to a multi-well small-pumping array will alter how the pumps are specified. Pumps should be the most efficient hydraulically and corrosion-resistant as possible and sized so that the selected models are close to their optimal pumping range on manufacturer pump curves.

On both the single-well and multi-well design options, horizontal pump discharge lines should be equipped with valved blow-off hydrants to permit easy recirculation well treatments, manual water quality sampling, and pumping tests in the future. Individual wells in the multi-well option should have individual controls and flow meters. Provision for manual as well as automatic SCADA water level measurements can be taken.

These recommendations are presented with the purpose of building as much prevention as possible in the design so that future well deterioration is significantly slowed, and easier to treat when it occurs. Multi-well and lower pumping rates are recommended to prevent the cascading and upper-screen oxidation now contributing to rapid well clogging. Optimizing screen efficiency will slow the effects of clogging. Installing blow-offs and individual controls and metering makes future maintenance easier.

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10. Prioritization and Budgeting of Recommendations

In a final decision-making process after the completion of project tasks, Technical Services Center (TSC) and consultant considered the numerous recommendations made (as presented in the preceding sections) in order to prioritize them in light of various limits and needs. In January 2000, TSC and consultant met and also considered a model budget for the Closed Basin Division (CBD) to implement recommendations. The following is a summary of these discussions and presented for consideration in CBD planning.

General AFO/CBD Prioritization

The following acts are ranked in general order of importance for maintaining water output:

1. Conduct Stage 3-5 triage (using spreadsheet as a simple guide to more complex actions), conduct rehabilitations needed and establish preventive maintenance actions (PM), using the Stage 3-5 PM plan (Section 7) as a guide: Included in that are the wellhead modifications and monitoring program acquisitions described.

a. Do the triage. Get to a manageable number of "good" wells.

b. Monitor in the optimal manner for PM, getting to verifiable monitoring data as soon as possible. This will really help focus the effort and help gauge progress.

c. Verify what works in rehabilitation (defining the contributions of various stages of the rehabilitation effort). This involves long-term monitoring of the selected "Laguna" and "BCHT" wells (Section 5).

Note that it is important to do the data gathering, because this is the only way to <u>know</u> what has happened.

2. Watch Stage 1-2 wells, modify the pumping as recommended (Section 6): This attitude of watchful waiting with minimal action for now should be sufficient, but the wells should not be neglected.

3. Work on organizing the well data for ease of monitoring and visualization: Proceed as recommended in Section 8, with the existing database system, spreadsheets and ArcView, watching the specific parameters. This should be done short-term, but will permit long-term evaluation.

4. Work up the cost-benefits of recommended actions: The cost-effectiveness of implementing maintenance and rehabilitation actions to optimize water output over the long haul should be an incentive both upstream to water users who will benefit as Colorado water can be retained in the state for consumptive use, and downstream to beneficiaries of the Closed Basin's output.

5. Stage in new construction as feasibility permits: Make the PM effort more worthwhile, permitting the elimination of unproductive wells, and installing wells that are easier to maintain.

Research and PM Implementation to Benefit CBD in the Near Term (2000-2002)

(1) Answer the question of the clog: Do the cone penetrometer sampling and material analysis discussed, develop preliminary physical and geochemical models, and conduct associated analyses.

(2) Conduct PM training and demonstration as recommended: This essentially encompasses the Section 5-7 PM monitoring and maintenance plans.

(3) Work toward "systemization" of the data analysis and gathering, using GIS, Access, spreadsheet tools.

Budget realities for 2000 will result in a short pause in efforts until more funds and personnel can be marshaled to the task. In this time period, expert consulting help, which has been concentrating on strategic planning in 1999-early 2000, can be used to refine and tweak the recommended program, advising on modifications as needed and offering training and guidance. Two major tasks are recommended:

(1) PM demonstration training, assistance, and supervision.
(2) Assist in GIS organization effort in advisory role: This is under way and will be completed by the end of the current contract period (end of July 2000).

Work that benefits CBD could have benefits for other water engineering projects (dam toe drains, for example) and vice versa. Project management would benefit all interests with maintenance needs by seeking opportunities for cooperation and synergy.

Specific Tasking for Budgeting

Data acquisition and management (Section 8)

These are roughly prioritized with commentary. Priorities are more order of work, not ranks of importance.

(1) Flow and water levels from telemetry (current):

(a) Develop or refine a reliability history of the flowmeters in the inventory and watch for signs of decay in accuracy due to clogging effects. Calibration of typical meters during the "intensive" monitoring recommended for selected wells in the PM plans should assist in this effort.

AFO effort: Understand this to be under way, with no additional staffing or effort for telemetry quality assurance (QA) management. Manual calibration would involve the flow testing efforts recommended in the PM plan reports.

(b) UWL data recommendations:

(1) Define static elevations in wells and calibrate transducer-read elevations to these zero points frequently.
(2) As the static elevations may vary seasonally or due to precipitation variations, it may be necessary to spot check static elevations manually to provide a valid calibration point.
(3) When transducer readings become unreliable, change the sensors as soon as possible.

AFO effort: Understand this to be under way, with no additional staffing or effort for telemetry quality assurance (QA) management. Manual calibration would involve the water level testing efforts recommended in the PM plan reports. We have an additional recommendation to modify wellheads (see Section 7): Extend water level access tube into well to the hatch level to permit *easy, quick, WL measurement from the surface. Define this elevation as '0'. No additional staff costs would be necessary. Levels can be taken going to/from other work.*

(2) Manual well hydrologic testing (2000-onward):

Sections 5 to 7 discuss valid pumping tests. Truly valid assessments of treatment results require valid pre- and post-treatment well pumping tests.

(a) Build the test-connection apparatus described in the Stage 3-5 PM plan (Section 7).

(b) Begin modifying wellheads as recommended for testing, starting with wells planned for service next, and moving on to wells designated for intensive monitoring.

(c) Build a series of orifice weirs or suitable flow meters, sized to the range of flow capacities, as recommended in Section 8.

(d) Obtain necessary training in testing methods.

AFO effort: Build 1-3 of the test-connection "jigs" depending on number they plan to do at once. Orifice weirs 1-3 with three orifice plates each. We can supply plans or ready-made orifice weirs and flow charts for them if necessary. We can conduct the training seminar including a heavy rehabilitation component. Estimated budgets are supplied at the end of this section.

(3) Using data in modifying triage decisions. With improved and ongoing data, the CBD should revisit the spreadsheet supplied with Section 7 and update the flow rates, static and pumping UWL, Q/s values (actual and potential), and add or subtract wells as needed.

AFO effort: Maintain spreadsheet in handy place, adjust as information becomes available and is evaluated. No additional staffing. Our input included in above.

(4) Biological testing and calculating a well fouling index.

(a) Work with Sangre de Cristo Laboratory (SDC) and consultant on protocol and testing.

(b) Develop well fouling index for "index" wells over a period of at least one year and probably several years.

AFO effort: Obtain SDC Labs price. Consultants can work out the protocol and prices with them if AFO prefers. The WFI would be another spreadsheet effort, assigning a percent-difference relationship between BART differences and Q/s differences once a data history is available.

(5) Charting and using GIS in evaluating data for PM.

(a) On the established Closed Basin base map and well locations in ArcView or equivalent:

(1) Plot static and long-term pumping UWL from wells, along with UWL from nonpumping monitoring points.

(2) Both lithology and stratigraphy should likewise be plotted to provide a more systematic model of the distribution of productive and nonproductive (e.g., clay) units in the basin.

(3) Plot useful indicator parameters such as total organic carbon, TDS, and metals, and calibrations such as Ca-Mg saturation indices.

(4) A similar plotting of percent changes in WFI can provide a means of analyzing the relative importance of clogging mechanisms at various points in the Closed Basin.

AFO/TSC effort: It appears that AFO has this capability and a hydrologist with ArcView experience. This could be a major effort, gathering and inputting information, however, as ArcView has a built-in Access version, data can be uploaded in the Alamosa office easily, then plotted. Inputting some external data and models could be more time-consuming. We would recommend assigning about a day per week to this task. The benefit to AFO is much easier visualization of Closed Basin well and aquifer conditions for analysis and presentation to decision-makers. We would suggest that the consultant or USBR geochemist conduct the PHREEQC modeling to obtain multi-parameter saturation values, and plot those. Plotting raw values would be needlessly confusing. Plotting WFI's will have to be delayed until a history is available. This work is professionally labor-intensive.

(b) Bring up, install and modify (as needed) the USGS a numerical model of the Closed Basin unconfined section.

(1) Test the effects of discrete changes such as dewatering at specific cells (representing individual salvage wells). Long term pumping effects under varying climatic conditions can be modeled in "real time."

(2) Overlay on the Closed Basin ArcView base map to permit comparison among parameters.

AFO/TSC effort: The Leonard and Watts (1989) USGS model is MODFLOW, and probably a valid model (their quality tends to be good). For present evaluation, the model may need to be formatted to modern Windows platforms (older versions of MODFLOW models can usually be picked up by the current software). The control points should be verified so that they can be assigned to known pumping or monitoring wells. USBR has its own hydrogeologist/modelers or request interagency from USGS.

Salvage Well Rehabilitation

(1) Permanent staffing recommendation:

(a) Two crews of two technically trained people in well maintenance and rehabilitation, having specific training for Stages 3-5 and one for Stages 1-2.

(b) Under the general maintenance supervisor, or reporting to him, a professional person in charge. This should be a very specific type of person.

(2) Contractor support: Contract a qualified and available well service firm, especially at the beginning to get up to speed (backlog), and for a "hump period" each year. Alternative: If more cost-effective, outsource everything if a valid proposal is made. This option can be explored via the request for proposal process. It would be beneficial for a professional maintenance contractor to contract local firms for field services.

(3) Training: It may be helpful to contract with a training provider to get specific training, or to hire Trinidad State graduates and run them through training specific to the planned PM and rehabilitation program.

AFO action: Budget the four people (at whatever that costs) and the equipment recommended in the Stage 3-5 PM plan. If it is desired to go all the way and institute BCHT, ARCC Inc. would *entertain a license plan. Budget to rehab/PM-treat 20-40 wells per year, including Sonar Jet as indicated. Get prices from contracting companies. Budget training.*

Proposed CBD Well Maintenance and Rehabilitation Budget

It is clear that maintenance difficulties and costs were grossly underestimated in the initial project feasibility planning (Department of Interior, 1970). Several maintenance issues that proved very important drains on time and resources were not foreseen (e.g., intense biological growth in the conveyance canal). It is recommended that these costs of O&M be reevaluated in detail.

The spreadsheet table following this section offers a budget proposal for consideration of the costs of proposed well rehabilitation and maintenance efforts. It identifies Tier 1 tasks, which are those that are primary in priority or need. The primary budget is based upon developing the recommended PM team augmented by contractor-supplied services (e.g., pulling and resetting pumps and well redevelopment). An alternative supplied is to develop a completely in-house capability, which has cost benefits, but depends on retaining a high level of skills and PM supervision expertise in Alamosa.

Water Costs and Benefits

In the planning process, it is necessary to justify costs such as these based on their benefits, which can be strictly economic or have a mixture of quantifiable and semi- or nonquantifiable characteristics. Helweg et al. (1983) and Jordan (1998) provide examples of benefit-cost calculations appropriate to this effort. While strict cost-benefit balances are valuable, U.S. Bureau of Reclamation (1992), in addressing the economic analysis of maintenance, recommends that such analysis include factors beyond mere economic return. In the case of the Closed Basin project, such a benefit would be reliable water output to meet Compact requirements. These requirements do not have an economic component.

However, benefits can be quantified in economic terms if dollar values can be placed on benefits using available methods in water economic value (e.g., Young and Gray, 1972). As a justification for the costs identified, it is recommended that

(1) A monetary value should be placed on the water pumped into the Rio Grande, using some value such as dollars per acre-feet of water available to upstream Colorado irrigators or potential downstream customers such as the City of El Paso (switching to surface water). The USBR uses similar environmental economic estimations of benefits in evaluating other projects (e.g., Ekstrand and Platt, 1999).

(2) Costs of pumping water be charted (kWh of power used, amortization of facilities, and maintenance costs). In this case, benefit (B) is a reduction in the cost of operation via the efficiency improvements gained through maintenance. As with the objective water data recorded in the system, these data can be recorded and updated, and calculations made using available spreadsheet software and formulas.

AFO/TSC effort: We recommend doing this very soon to assist AFO in its budgeting and staffing requests.

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The contributions to this prioritization and budgeting effort by TSC personnel Rod Tekrony, Jack Cunningham, Sarah Wynn, and John Ellis, who organized the process, are gratefully acknowledged.

Section Attachment: Closed Basin Division Well Maintenance and Rehabilitation Budget.

Appendix

Information in support of Analyses, Conclusions and Recommendations

Chapter 2: Log information and communications

Chapter 3:
SW 84, SW 99, and SW 103 Information

(1) Construction and background performance information

(2) Test and analysis information, SW-99 pre-treatment step test

(3) Test and analytical information, CBD-conducted SW-84, -95, -99, and -103 post-treatment step tests and flow data.

Clog treatment analytical Information

(1) Elemental and mineralogical analysis of SW 99 and SW 103 solids

(2) Jar test detailed results

Field notes from August 1999 BCHT field demonstration and testing

(1) Jack Cunningham, TSC
(2) John Ellis, TSC
(3) Stuart Smith (Smith-Comeskey)

Chapter 7:

(1) Results of September 21 to 24, 1999 tests of cleaned wells, conducted by CBD.
(2) Flow and UWL data supplied by the CBD.
(3) Charts of Flow and UWL trends supplied by CBD
(4) Well data and recommendations spreadsheet supplied on disk

Jar test detailed results, SW 99 and SW 103 solids, May and June 1999 (2 pp. table)

Test	Date	Solution	initial pH	final pH	elapsed time	Description
1	5/29/99	1 % Citranox	2.6	3.2	3 hr	SW99 solids. Started as creamy suspension, little dissolution, fine materials stay in suspension, with 8 mm settlement.
		1 % Citranox + 5 % HCl	0.2	0.6	3 hr	SW99 solids. Immediately began to dissolve (foamy iced tea mix). Small particles remain suspended. 2 mm of settlement at end. Small-diameter glassy iron particles (microscopy).
		5 % HCl	< 0.1	0.5	3 hr	SW99 solids. Immediately began to dissolve (foamy iced tea mix). Small particles remain suspended. Also dissolved a second 10 g of solids. 2 mm of settlement at end. Small-diameter glassy iron particles (microscopy).
2	5/29/99	1 % Citranox	2.6	6.5	20 hr	SW103 solids. Started as creamy suspension, little dissolution, fine materials stay in suspension, with 8 mm settlement. Microscopy: some mineral dissolution, filament holdfasts become visible, loose bacteria in motion.
		1 % Citranox + 2.5 % HCl	0.8	0.5	20 hr	SW103 solids. Immediately began to dissolve ("back coffee" appearance). Only small dispersed mineral particles remain at test end. 5 mm of settlement at 2 hr and 2 mm at end.
		5 % acetic	2.6	3.2	20 hr	SW103 solids. Gray, cloudy suspension. At end, very little change in solids structure, no dissolution of bacterial structures. 5 mm of settlement at end.
3	6/1/99	1 % Citranox + 5 % acetic	2.6	3.2	22 hr	SW99 solids. Mostly suspended solids with ~ 5 mm sediment, mostly throughout test. Suspended phase: broken filaments and fine silt. Settled phase: larger Fe oxide particles, sediment.
		1 % Citranox + 10 % acetic	2.4	2.8	22 hr	SW99 solids. Mostly similar results.
		1 % Citranox + 15 % acetic	2.3	2.7	22 hr	SW99 solids. Mostly similar results.
4	6/2/99	1 % Citranox + 5 % acetic, HCl acidified	1.4	2.3	22 hr	SW99 solids. Mostly suspended solids with ~ 10 mm sediment, mostly throughout test. Little structure alteration.
		1 % Citranox + 10 %	1.5	2.2	22 hr	SW99 solids. Mostly suspended solids with ~ 10 mm sediment,

		acetic, HCl acidified				mostly throughout test. Little structure alteration. Smaller "pin floc" than 5 % test.
		1 % Citranox + 15 % acetic, HCl acidified	1.5	2.1	22 hr	SW99 solids. Mostly suspended solids with ~ 10 mm sediment, mostly throughout test. Visibly flocculated particles. Solids settled more quickly.
5	6/3/99	1 % Citranox + 5 % acetic, HCl acidified	1.7	2.2	8 hr	SW103 solids. Mostly suspended solids with ~ 3 mm sediment, dark gray "sun tea" appearance. Dispersed dark rounded oxide particles, *Gallionella* stalks.
		1 % Citranox + 10 % acetic, HCl acidified	1.5	2.5	8 hr	SW103 solids. Good suspension, < 2 mm settled solids.
		1 % Citranox + 15 % acetic, HCl acidified	1.5	1.9	8 hr	SW103 solids. Good suspension, < 2 mm settled solids. Note: Slow settling to clarity over 5 d, with mostly mineral silt left.
6	6/8/99	1 % Citranox + 2.5 % HCl	0.6	0.7	6 hr	SW103 solids. Dark suspension. 3 mm settling of solids.
		1 % Citranox + 5 % HCl	0.4	0.5	6 hr	SW103 solids. Completely oxidized (yellow color). No settling of solids.
		1 % Citranox + 15 % acetic, HCl acidified	1.3	1.5	6 hr	SW103 solids. All suspended dark solids. 8 mm settling of solids.

Field notes from August 1999 BCHT field demonstration and testing

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(2) John Ellis, TSC

(3) Stuart Smith (Smith-Comeskey)