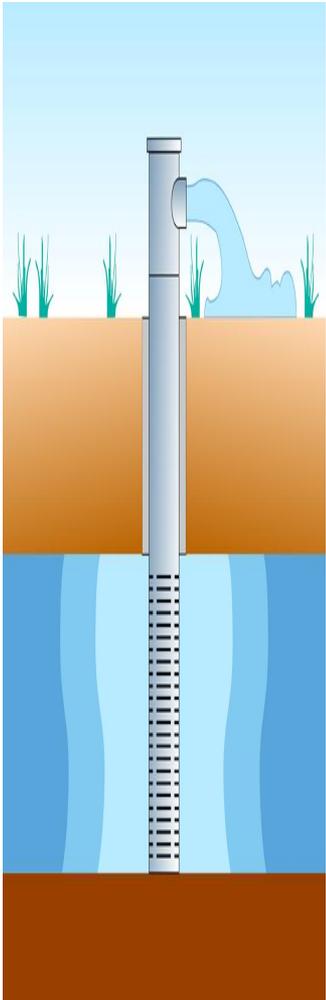


Aquifer Storage Recovery (ASR) Workshop



17th Biennial Symposium on Managed Aquifer Recharge (BSMAR17)

October 6, 2020

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www.asrsystems.ws



Housekeeping Details

- Questions and Answering Process
 - Anytime via “chat” message
 - Responses between each of the five “sessions”
- Ten-minute break in middle
- Email to dpyne@asrsystems.ws if you need certification for 4 hours of CEU credits and did not note that on the conference registration form, or if you have any follow-up comments/questions.
- Stop at 4 hours. Last segment on ASR Economics is flexible and content will depend on available remaining time



ASR Workshop Outline

Tuesday October 6, 08:00 to 12:00

1. Introduction to Well Recharge/ASR
2. Phased Approach to Successful ASR
ASR Applications
Key Principles for Successful ASR
3. Science/ Technology
Design of ASR Wells and Wellhead Facilities
4. Well Conditioning and Operation of ASR Wells and Wellhead Facilities
5. ASR Economics/ Regulatory (optional, time permitting)



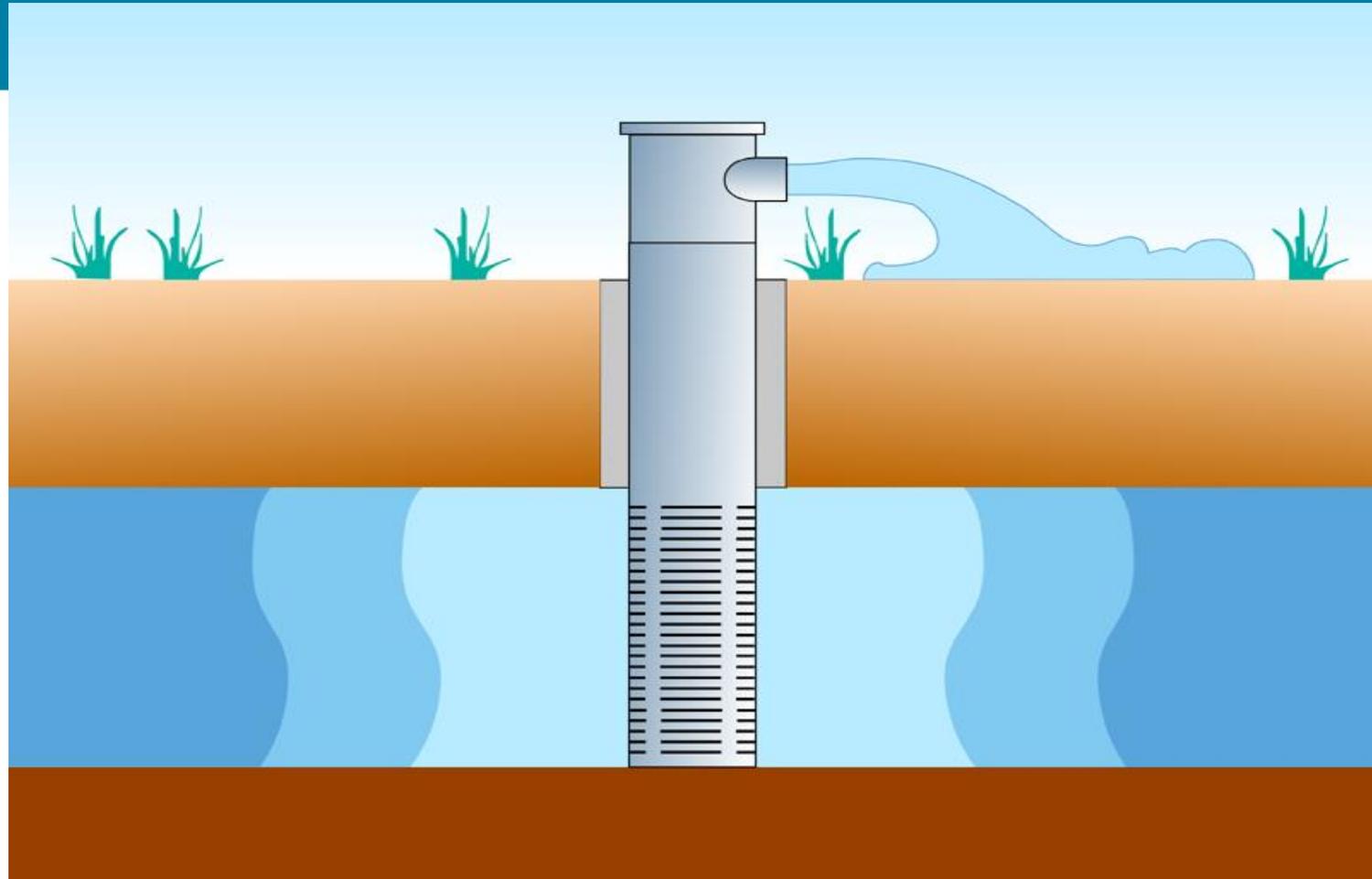
Well Recharge Terminology

- **Aquifer Storage Recovery (ASR) wells**
 - Dual-purpose wells for aquifer storage and recovery from same well
- **Injection wells and Recharge Wells**
 - Single purpose wells for aquifer recharge and/or water disposal
- **Vadose Zone (“dry”) wells**
 - Deep water tables
- **Aquifer Storage Transfer Recovery (ASTR) wells (Australia)**
 - Multiple-barrier natural treatment and storage
- **Dual-Infiltration wells (Netherlands)**
 - Natural treatment; no storage
- **Others?** (Subsurface Water Storage; HDD wells; Freshkeeper wells)
- All are subsets of **“Managed Aquifer Recharge”**



Aquifer Storage Recovery...

“Managed Aquifer Recharge” Through Wells



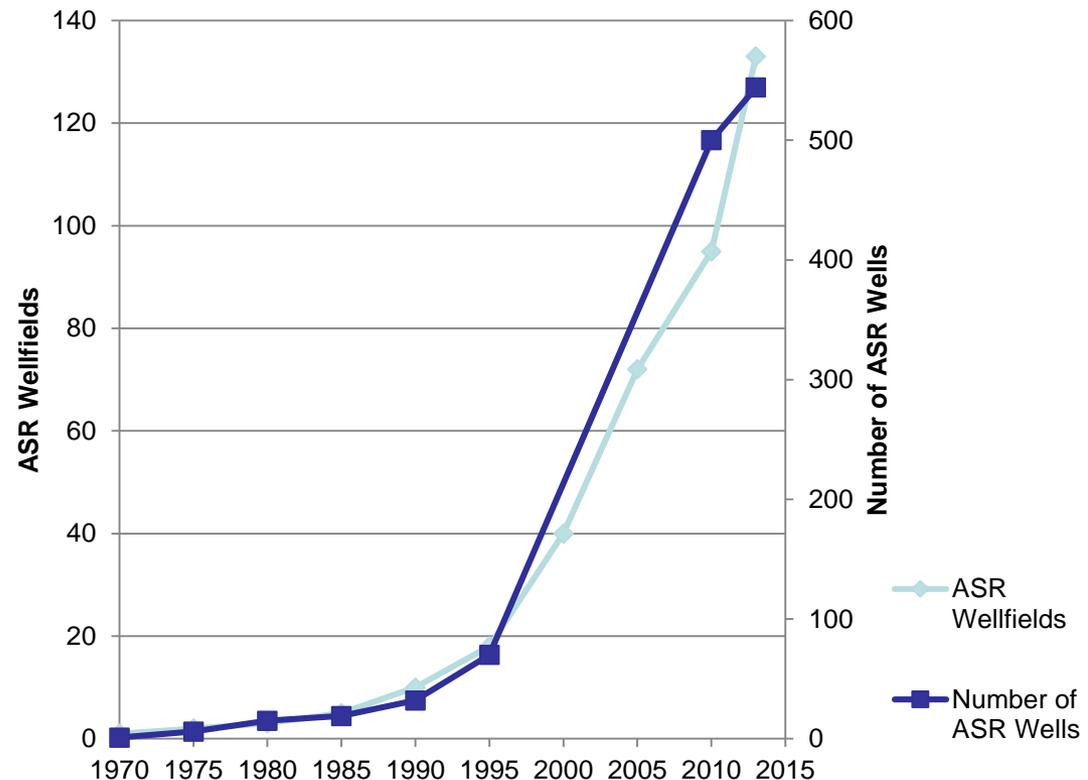
Storage of water through a well in a suitable aquifer during times when the water is available, and recovery of the stored water from the same well when needed



ASR Development has been rapid during the past 25 years

- Currently (2020) at least 500 ASR wells operating in at least 140 ASR wellfields in at least 25 states in USA
- Many other countries as well
- 30 different types of ASR applications
- Many different types of water sources for aquifer recharge
- Storage in many different types of aquifers and lithologic settings

ASR Historical Development in USA



California ASR Wellfields

- CALLEGUAS MWD
- EAST BAY MUD
- ORANGE COUNTY WATER DISTRICT
- GOLETA WATER DISTRICT
- JURUPA COMMUNITY SERVICE DISTRICT
- LONG BEACH
- MONTE VISTA WATER DISTRICT
- MONTEREY PENINSULA WMD
- PLEASANTON, ZONE 7, LIVERMORE
- ROSEVILLE
- SANTA CLARA COUNTY WATER DISTRICT
- TRACY
- CARPINTERIA VALLEY
- VALLEY WATER DISTRICT
- VICTORVILLE
- WOODLAND
- OXNARD
- WESTLANDS WATER DISTRICT



Woodland CA – ASR Well 29

Estimated 18 ASR wellfields in California



Arizona ASR Wellfields

- Chandler Octavio
- Chandler Tumbleweed
- Chandler Intel
- Far West W&S
- Fountain Hills
- Gilbert
- Glendale Arrowhead Ranch
- Phoenix Cave Creek
- Sun Lake City- Pima Utilities
- Sun Lake City- West
- Lake Pleasant
- Scottsdale Water Campus
- Phoenix
- Tempe



Chandler, AZ
Tumbleweed ASR Wellfield
Storing Reclaimed Water for Aquifer Recharge

Estimated 52+ ASR Wells at 14 ASR wellfields in Arizona



Global implementation of ASR since 1985 to achieve water supply sustainability and reliability

- Australia
- India
- Bangladesh
- Israel
- Canada
- England
- Netherlands
- South Africa
- Namibia
- United Arab Emirates
- And others in development
 - (Kuwait, Taiwan, Indonesia, Qatar)



Adelaide, Australia ASR Well



ASR Projects are Getting Larger

- Early ASR projects met local needs with one or more ASR wells.
- Subsequent ASR projects have been developed to meet larger, regional needs with a greater number of ASR wells.
- Future ASR projects are being planned to meet regional/ national needs with wellfield capacities of up to 400 MGD for 90 days (110,000 AFY, 1.5 Mm³/D)



Several factors have contributed to ASR global implementation

- Economics
 - Typically less than half the capital cost of alternative water supply sources
 - Phased implementation
 - Marginal cost pricing
- Proven Success
 - At least 140 wellfields in 25 states in the USA, with over 500 operating, fully permitted ASR wells
- Environmental and Water Quality Benefits
 - Maintain minimum flows
 - Conjunctive use with surface reservoirs for flood control
 - Small storage footprint compared to surface reservoirs
- Adaptability to Different Situations
 - Over 30 different applications



*Mt Pleasant, South Carolina
Well ASR-2*

A broad range of water sources and storage zones is utilized for ASR

- Water sources for ASR storage
 - Drinking water
 - Reclaimed water
 - Seasonally-available rainwater/ surface water
 - Groundwater from overlying, underlying or nearby aquifers
- Storage zones
 - Fresh, brackish and saline aquifers
 - Confined, semi-confined and unconfined aquifers
 - Sand, clayey sand, gravel, sandstone, limestone, dolomite, basalt, conglomerates, glacial deposits
 - Vertical “stacking” of storage zones



ASR Operating Ranges

- Well depths
 - 180 to 3,000 feet
- Storage interval thickness
 - 20 to 500 feet
- Storage zone Total Dissolved Solids (TDS)
 - 30 mg/l to 35,000 mg/l
- Storage Volumes
 - 100 AF to 100,000+ AF
- Bubble radius usually less than 1,000ft
- Individual wells up to 8 MGD capacity
- Wellfield capacity up to 157 MGD
- Planned capacities up to 400 MGD

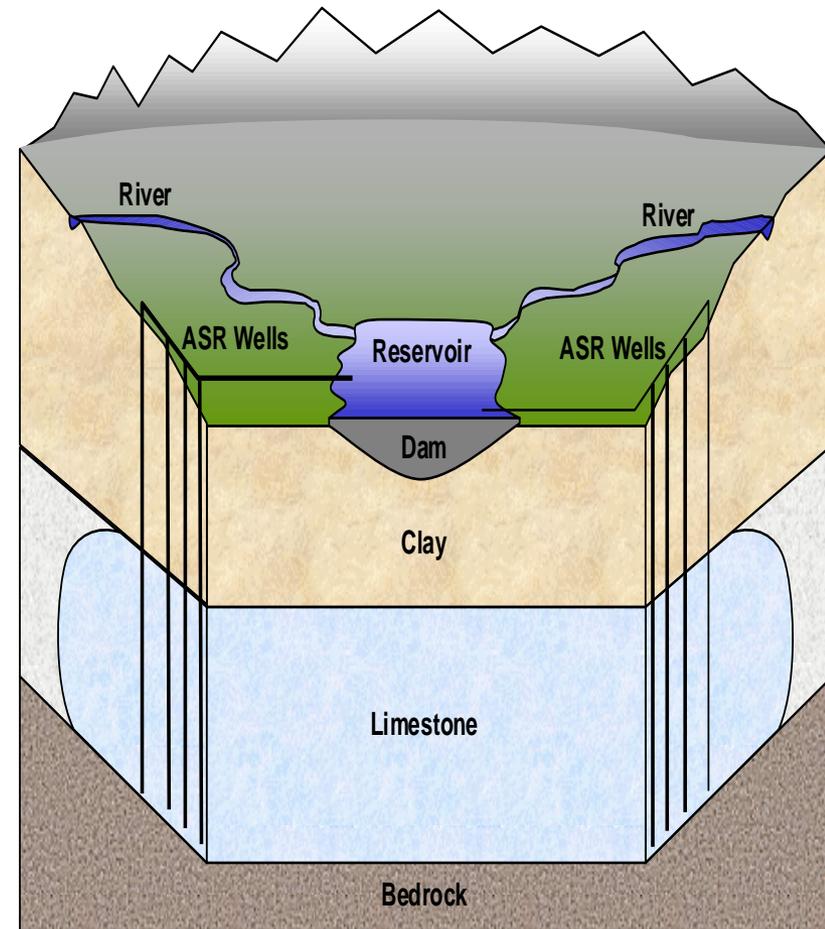


*Calleguas Metropolitan
Water District, California
ASR Well*

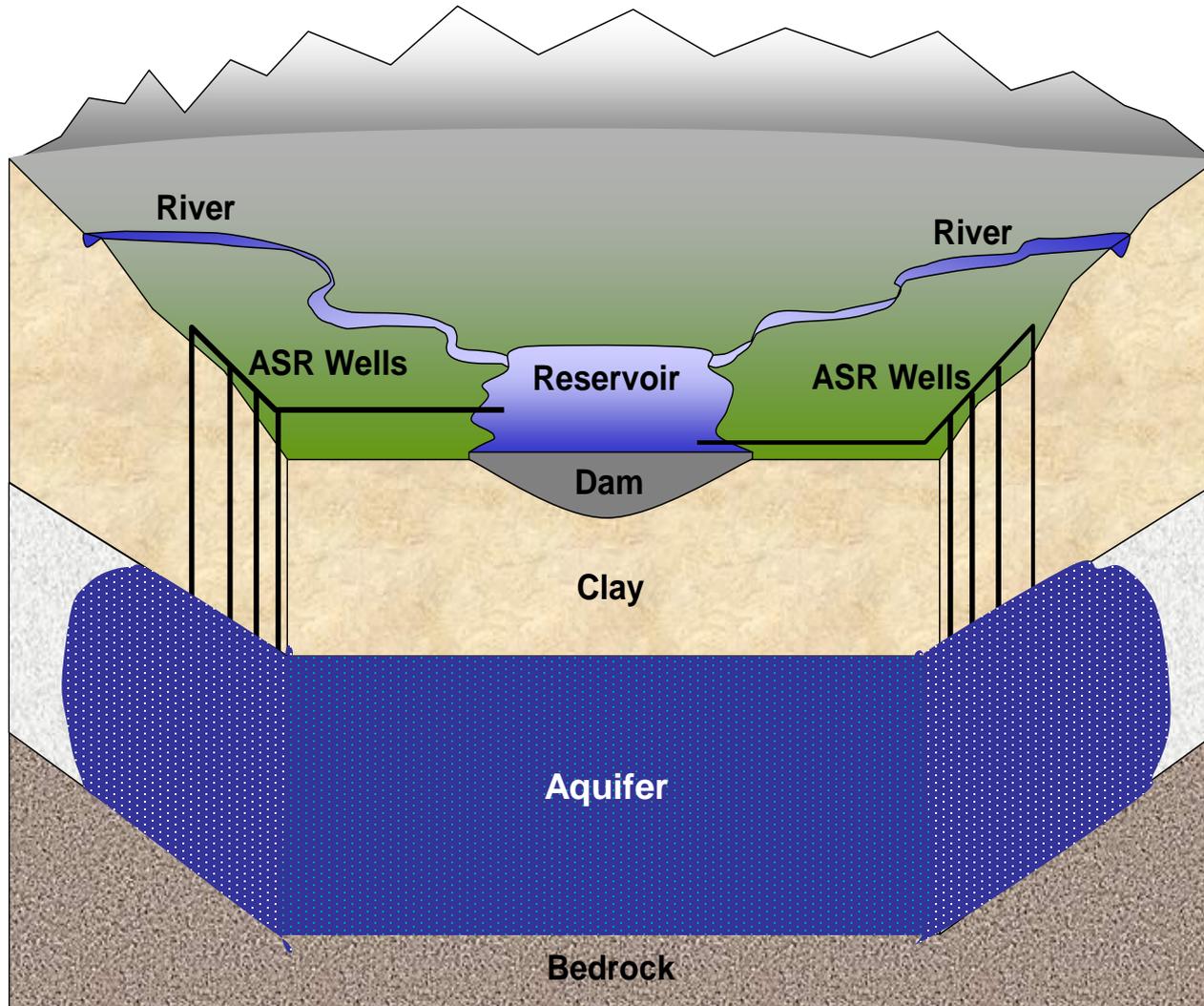


A combination of ASR wells and surface reservoirs is very beneficial for providing water storage

- Surface reservoirs capture water quickly, but...
 - are expensive
 - require a lot of land
 - often significant evapotranspiration and seepage losses
 - Often have environmental opposition
- Where feasible, ASR wells can store much larger volumes of water
 - occupy little land
 - can be built in increments
 - have few losses, but can only recharge and recover water slowly



The combination of aquifer storage and surface reservoir storage is cost-effective for achieving water supply reliability and sustainability.



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Following a proven, phased approach leads to successful well recharge system development while minimizing risk

- **Define Objectives**
 - Define and prioritize (30 ASR applications to date)
- **Phase One: Feasibility Assessment**
 - Typically 4 to 6 months' duration
 - Deliverable: Feasibility Assessment Report
- **Phase Two: Field Investigations**
 - Typically 24 to 36 months' duration
 - Construct one or more full size, operational, ASR wells and monitor wells, and maybe a core hole
 - Deliverable: Operating ASR well(s)
- **Phase Three: System Expansion**
 - Often in 2 or more stages. Learn from experience.
- **Reasons for fewer or greater number of phases**



ASR Phase One Feasibility Assessment: Typical Outline

- Select/ prioritize objectives
- Historic and projected water demands and variability
- Water supply availability
- Water quality variability and treatment requirements
- Storage volume requirements to meet reliability goals
- Hydrogeology
- Geochemistry
- ASR concept plan/ prelim design
- Economics
- Legal, regulatory, institutional considerations



*Beaufort-Jasper Water and Sewer
Authority, South Carolina*

Well ASR-1



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ASR Applications / Objectives

- The number of ASR applications is steadily increasing... currently 30
- Lack of awareness of these potential applications is often a major constraint upon effective ASR implementation
- Identifying and prioritizing ASR objectives provides a firm basis for subsequent selection of wellfield sites and storage aquifer(s)



Example: Victoria, Texas

Potential ASR Objectives (1/2)

Select and Prioritize One or More Pertinent ASR Applications for each ASR wellfield:



Kiawah Island, South Carolina



Centennial WSD, Denver, Colorado

- **Seasonal storage**
- **Long-term storage (“water banking”)**
- **Emergency storage (“strategic water reserve”)**
- **Diurnal storage**
- **Disinfection byproduct reduction**
- Restore groundwater levels
- Control subsidence
- **Maintain distribution system pressures**
- **Maintain distribution system flow**
- Aquifer thermal energy storage (ATES)



Victoria, Texas

Potential ASR Objectives (2/2)

- Reduce environmental effects of streamflow diversions
- Agricultural water supply
- Nutrient reduction in agricultural runoff
- Enhance wellfield production
- **Defer expansion of water facilities**
- Reclaimed water storage for reuse
- Stabilize aggressive water
- Hydraulic control of contaminant plumes
- **Maintenance or restoration of aquatic ecosystems**



*Manatee County, Florida
ASR Well, 1983*

ACEC Grand Award, 1984



Victoria, Texas

Selection and Prioritization of Objectives

1. Seasonal Storage
2. Long-term storage for “Drought of Record”
3. Defer water treatment plant expansion
4. Emergency storage
5. Reduction in disinfection byproducts



St. Petersburg, Florida

*Reclaimed Water ASR Well -
Southwest*



Seasonal Storage

- Usually an important benefit of ASR, in addition to providing long term storage.
- Annual benefit, not just once in a lifetime.
- Facilitates more efficient use of existing infrastructure, meeting peaks from ASR instead of from water treatment plants and transmission pipelines.



*Orangeburg,
South
Carolina*

*Total
6.5 MGD
(25 MI/D)*

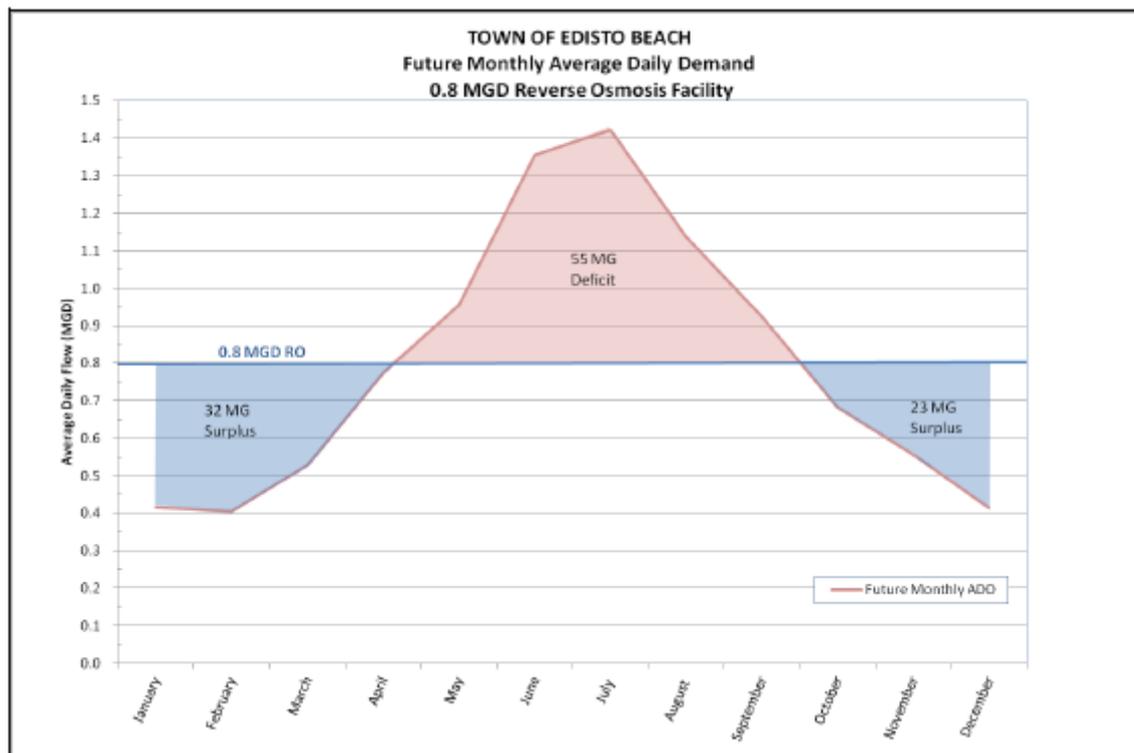


*Two ASR wells in two different
aquifers within a single wellhouse*



Store water in winter months and recover in summer months

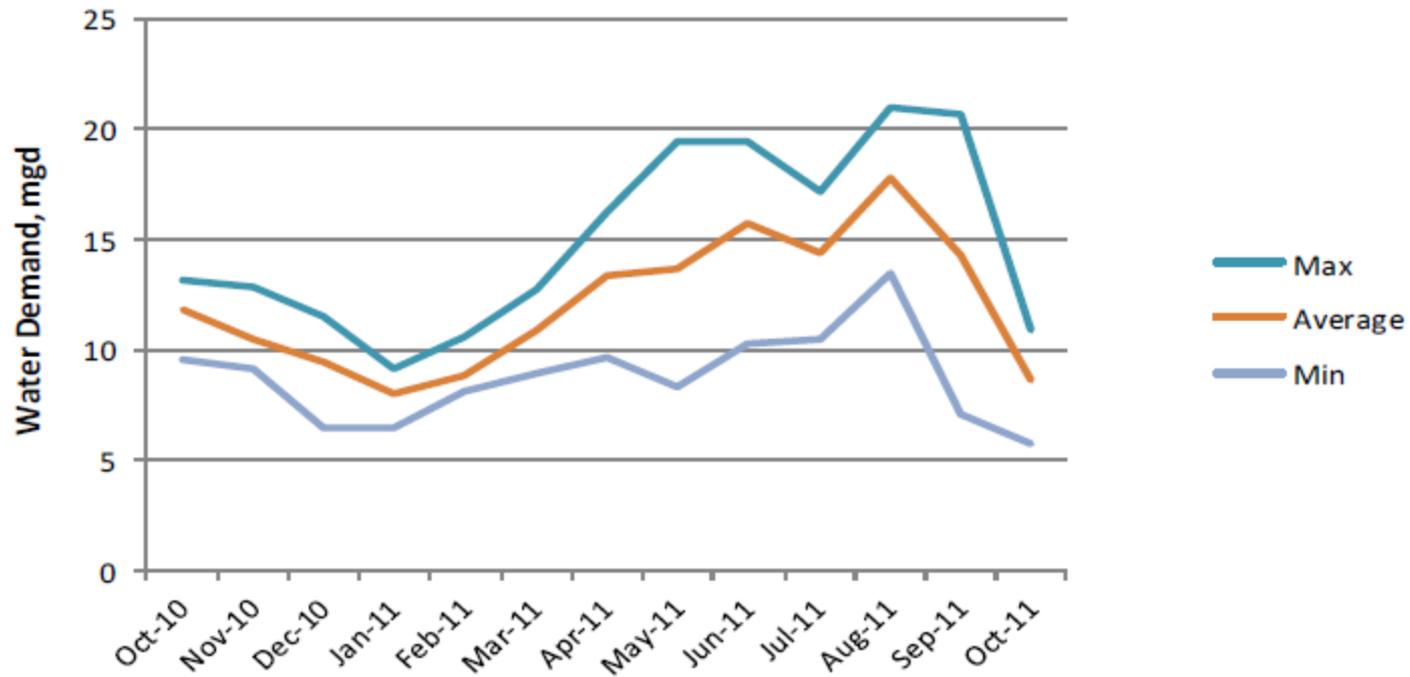
WATER DEMAND



MONTH



New Braunfels, Texas Monthly Water Demand Variability 2010 - 2011

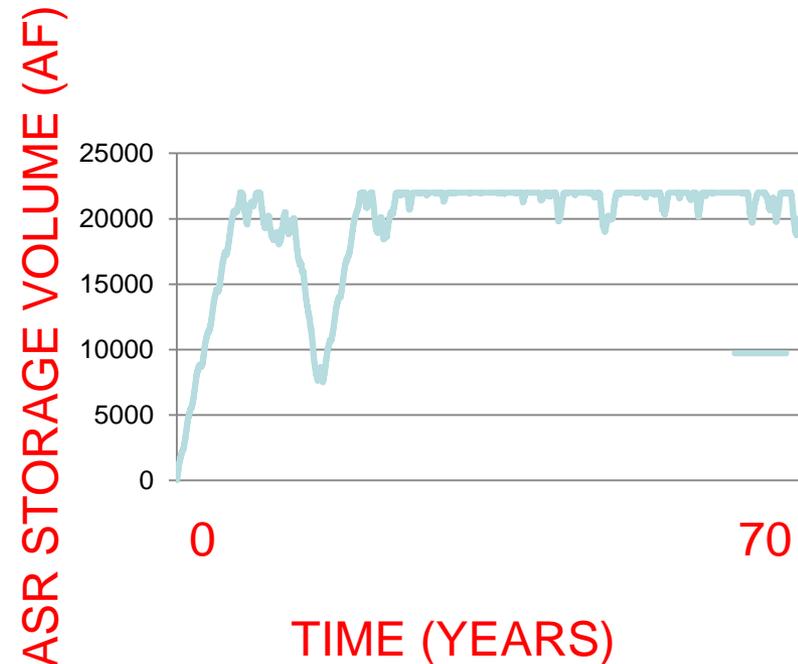


Note considerable opportunity for ASR storage, even during summer months



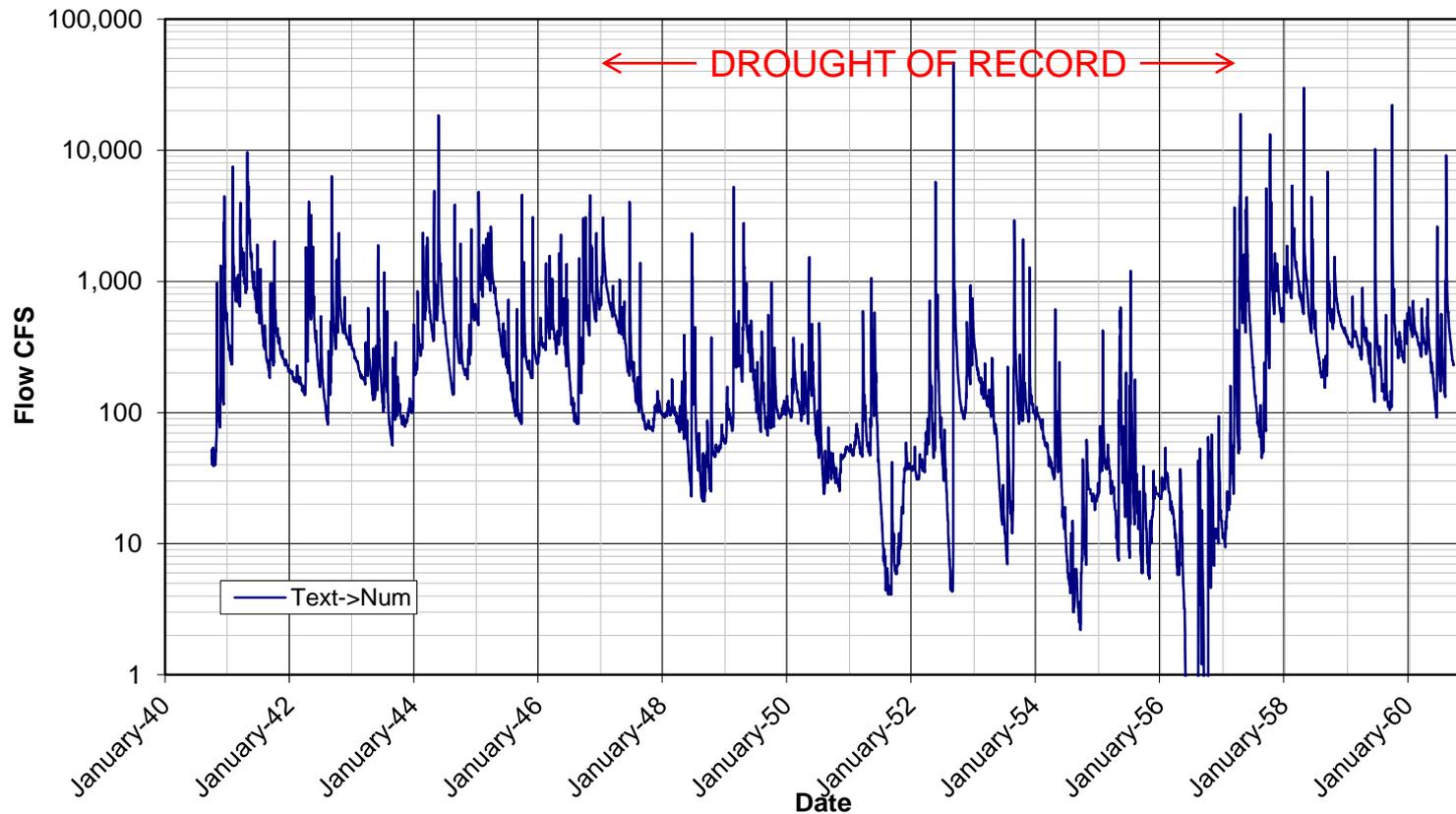
Long-term storage, or Water Banking for a possible repeat of the “Drought of Record”

- Brackish confined storage aquifer, 8,400 mg/l TDS
- How to estimate the Target Storage Volume (TSV)
- “Will the stored water still be there when we need it?”
- Lateral velocity of groundwater in the storage aquifer(s)?
- Proximity of other groundwater users?
- Potential impact on flow at Comal Springs
- Measures available to protect availability of the stored water



Even during the Drought of Record there were many high flow events

Guadalupe River Stream Flows, Texas



Strategic Storage for Emergencies

- Water systems dependent upon a single source and/or a long transmission pipeline
- Accidental loss, contamination, warfare, terrorism, natural disaster
- Build one or more strategic water reserves deep underground



*Des Moines Water Works, Iowa – 100 MGD WTP
Before and After 1993 Flood*



Emergency Storage: Des Moines ASR Objectives



Second deepest ASR well in the world – 2700 ft in Jordan Sandstone Aquifer

Retrofit of Existing Abandoned Production Well

Primary ASR Objective
Emergency Water Supply
30 MGD for 90 days – 2.7 BG

Secondary ASR Objective
Seasonal Water Storage
10 MGD for 90 days – 0.9 BG

Tertiary ASR Objective
Eliminate need for nitrate
removal during spring thaw



Emergency Water Supply - South Island Public Service District, Hilton Head, SC

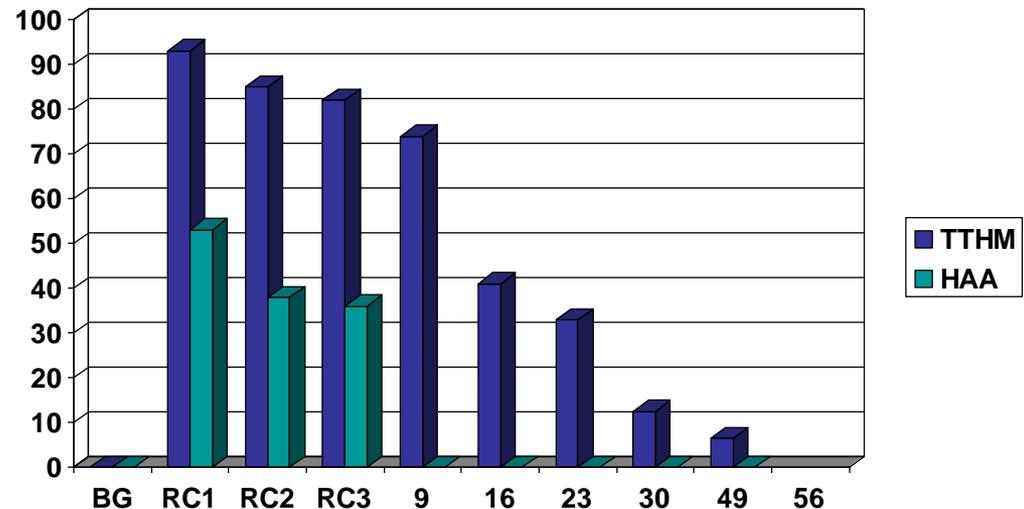


Palmetto Bay ASR Well, constructed seven feet below the hurricane coastal surge protection elevation



Disinfection Byproduct Reduction

- Elimination of **Haloacetic Acids** and their formation potential in a few days due to aerobic subsurface microbial activity
- Reduction of **Trihalomethanes** and reduction of their formation potential in a few weeks due to anaerobic subsurface microbial activity
- **Brominated THMs attenuate first, then chloroform**



Disinfection Byproduct Attenuation –
Centennial WSD, Highlands Ranch, CO



Maintain pressures, flows and water quality in a distribution system

- Keep the water moving
- Locate ASR wells in seasonal low-pressure areas such as at the top of a hill, the end of a long transmission pipeline, or a summer beach resort.
- Avoid the need for flushing pipelines to waste to maintain water quality in distal portions of a water distribution system

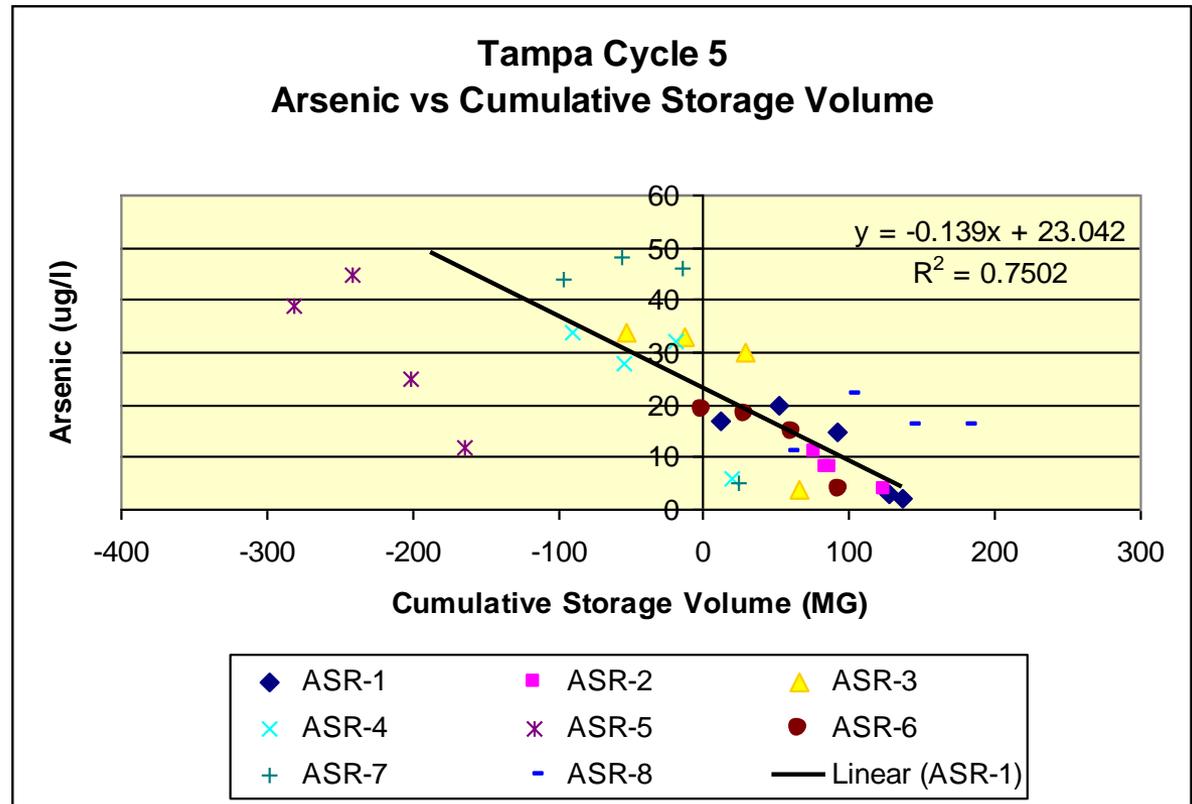


*Murray Avenue ASR Well
Cherry Hill, New Jersey*



Improve Water Quality

- Arsenic
- Fluoride
- Salinity
- THM and HAA
- Fe and Mn
- H₂S
- N & P
- TOC (carbon sequestration)
- Microbiota
- pH stabilization
- Temperature



Arsenic Decreases as the Cumulative Storage Volume Increases



Defer expansion of water facilities

- Operate treatment facilities to meet slightly more than average demands, providing for maintenance periods and times of inadequate supply
- Meet maximum day demands from ASR wells; peak hour demands from elevated and ground storage tanks
- Reduce capital costs by typically more than 50%



*Highlands Ranch, Colorado
One of 26 ASR wells underground
in vaults*



Hydraulic Control of Contaminant Plumes

- Oilfield injection well disposal of produced water through old, carbon-steel cased wells that may have corroded
- Other contamination sources (nitrates, chlorides, etc.)



Marathon, Florida

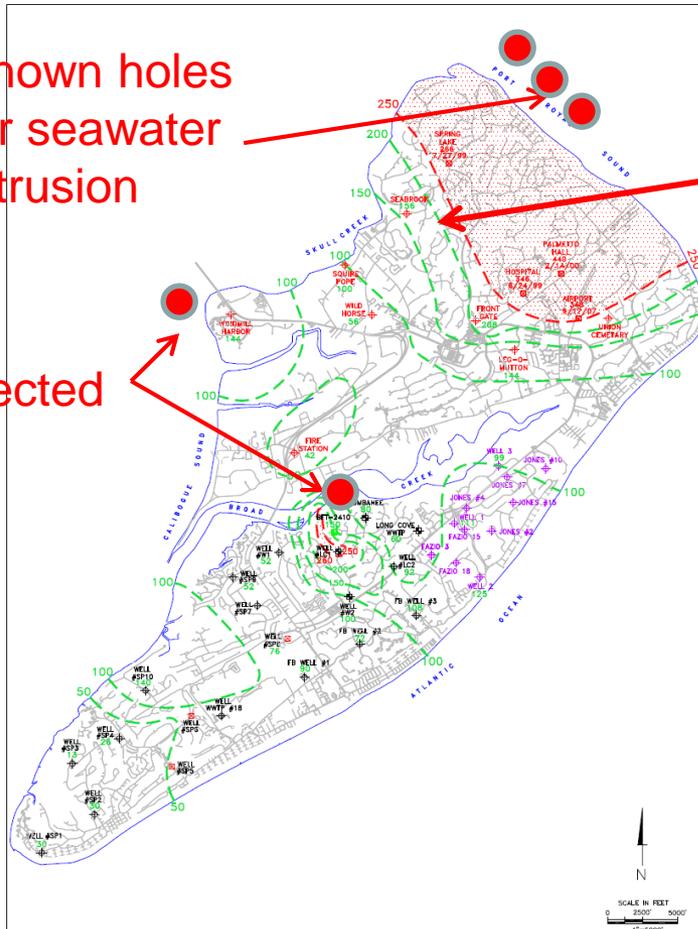
The first ASR well to successfully store drinking water in a seawater aquifer



Hilton Head Island, South Carolina Upper Floridan Aquifer Seawater Intrusion

Known holes
for seawater
intrusion

Suspected
holes



HILTON HEAD PSD WELL ASR-1

OPERATIONAL WITHIN 23 MONTHS

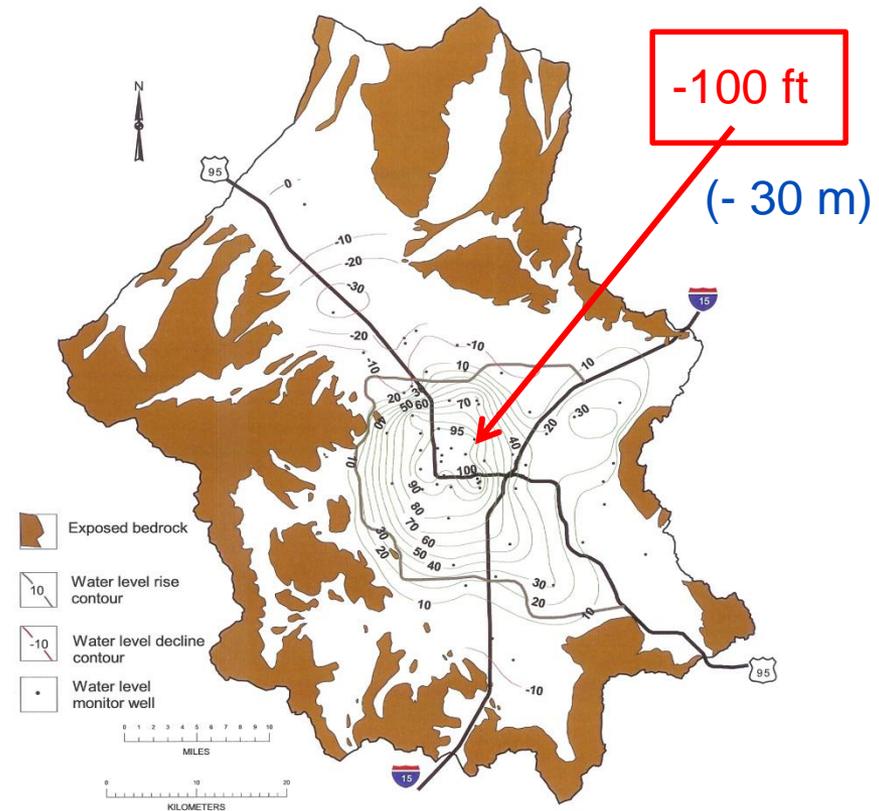


UFA=UPPER FLORIDAN AQUIFER		CHLORIDE CONCENTRATION CONTOUR 250mg/L CHLORIDE CONCENTRATION CONTOUR SCNCEC UFA MONITORING WELL OFF LINE UFA WELLS NEW UFA MONITORING WELL		30 CHLORIDE CONCENTRATION VALUE <250mg/L 250 CHLORIDE CONCENTRATION VALUE >250mg/L	 Date: 8/27/2010 Figure: 2
LEGEND HILTON HEAD PSD UFA WELLS BROAD CREEK PSD UFA WELLS SOUTH ISLAND PSD UFA WELLS	CHLORIDE CONCENTRATIONS IN HILTON HEAD ISLAND UPPER FLORIDAN AQUIFER WELLS (JUNE–AUGUST 2010)				



Several Other Potential ASR Objectives: Restore Groundwater Levels

- Applicable for areas where regional reduction in water levels has occurred due to pumping significantly exceeding natural recharge for many years
- Aquifer recharge also helps to control subsidence



(water level decline, negative: water level rise, positive)

Las Vegas, Nevada – Feet change in potentiometric surface of principal aquifer, 1990 to 2005



Restore Groundwater Levels: Las Vegas Valley Water District ASR Well 33



ASR Wellfield Recovery Capacity – 157 MGD from about 100 wells

Largest ASR wellfield in the world



Augmentation of Low Flows and Maintenance of Lake Levels

- Divert water during high flows and store underground
- Reduce or eliminate diversions during low flows
- Utilize a portion of the stored water for flow augmentation and the remainder to help meet other water needs during dry periods.
- Significant potential environmental benefits



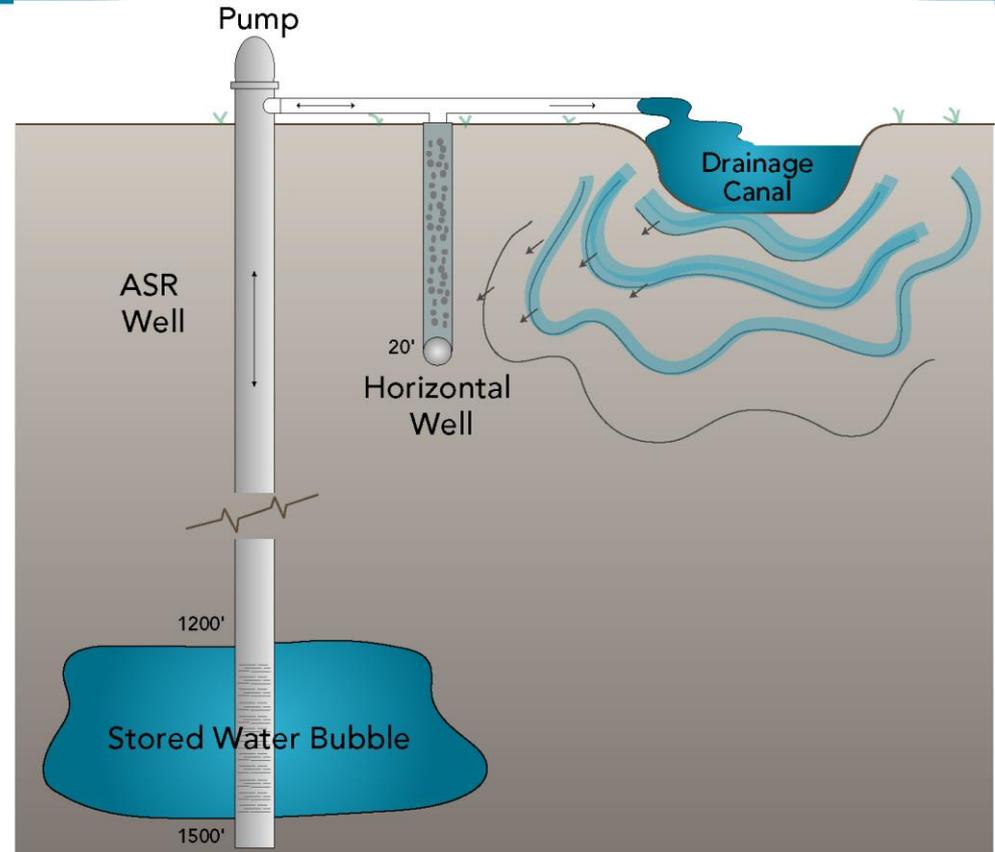
**Orange County Utilities ASR-1
Florida 2010**



Agricultural Water Supply:

Bank Filtration, Soil Aquifer Treatment, or Screening, Pressure Filtration, Disinfection and ASR

- Tailor ASR technology and science to meet agricultural needs, constraints and opportunities
- Consider bank filtration and soil aquifer pretreatment prior to ASR storage
- Major activity in Oregon, California, potentially also in Mississippi



Surface water is filtered through shallow sands to a horizontal well or underdrain and is then pumped to ASR storage



Thermal Storage

- Store cold water in winter for recovery during summer, reducing bacterial regrowth in distribution systems
- Industrial applications such as for process temperature control for microchip production, fish hatcheries
- Aquifer/Borehole Thermal Energy Storage (ATES/BTES) for heating and cooling buildings



*Marathon, Florida Keys, Florida
First ASR well to successfully
store drinking water in a seawater
aquifer*



Reclaimed Water Storage for Reuse

- Steady, reliable supply of reclaimed water
- Variable demand for irrigation water
- Seasonal opportunity for storing and recovering reclaimed water to meet peak irrigation demands
- Aquifer recharge of reclaimed water to achieve sustainable water supplies or to build a salinity intrusion barrier, or both



*Englewood Water District, Florida
Reclaimed Water ASR Well*



*City of Chandler, Arizona
Tumbleweed Reclaimed ASR Well*



Other ASR Possible Objectives

- Diurnal storage
- Reduce nutrients in agricultural runoff
- Enhance wellfield production
- Stabilize aggressive water
- Maintain or restore aquatic ecosystems
- Achieve water supply reliability and sustainability



*West Palm Beach, Florida
ASR Well – 8 MGD Capacity
Largest ASR Well in the World*



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Some Key Technical Factors to Achieve ASR Success

- ASR Feasibility Assessment
 - (Too often skipped)
- Geochemistry
- Appropriate Design and Equipping of Wells, and Design of Wellhead Facilities
- Variable frequency drive
- Downhole flow control
- Sealed wellhead flange
- Target Storage Volume and Buffer Zone
- Recovery Efficiency
- Interim Recharge
- Well Conditioning for Recharge
- Clogging, Backflushing, Redevelopment
- Cycle Testing and Stress Test



Kerrville Texas – ASR-1



Non-technical factors...

- Water is power. The control of water is therefore the currency of personal, regional and national ambitions
- Follow the money
- Legal, regulatory and institutional constraints and opportunities
- Public opinion



Reclaimed ASR Well, FL



Oxnard Advanced Water Purification Facility, CA



Geochemistry for ASR wells

- Read Chapter 5 in ASR book
- Perform geochemical preliminary analysis during ASR feasibility study using available published data & local experience
- Supplement with lab tests on cores or drill cuttings
- Update analysis based on new data from baseline water quality samples from ASR wells; cores and core analysis; recharge water analysis; geophysical logs.
- Estimate and form buffer zone volume.
- Analyze initial cycle test data and make adjustments, if necessary.
- Pros and cons of geochemical analysis for ASR wells



Appropriate Engineering Design for ASR Wells

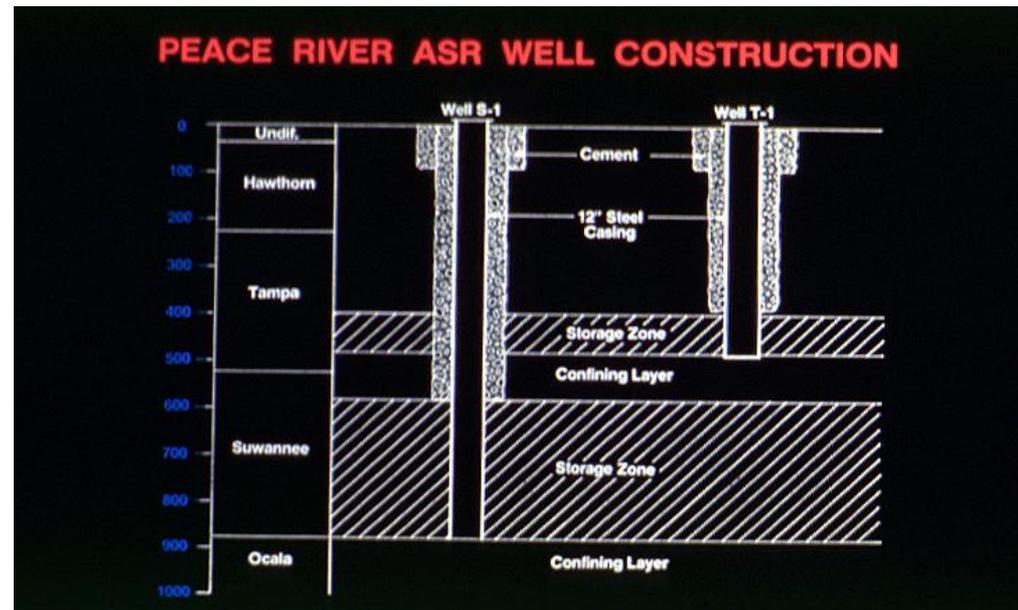
- Unique design considerations for ASR and recharge wells
 - Materials of construction
 - Casing/ borehole diameters
 - Storage interval(s)
 - Stacking, confinement
 - Annulus recharge
 - Monitor tubes & alignment
 - Screen design (strength)
 - Filter pack selection
 - Grouting

**New Braunfels, Texas
Well ASR-D1**

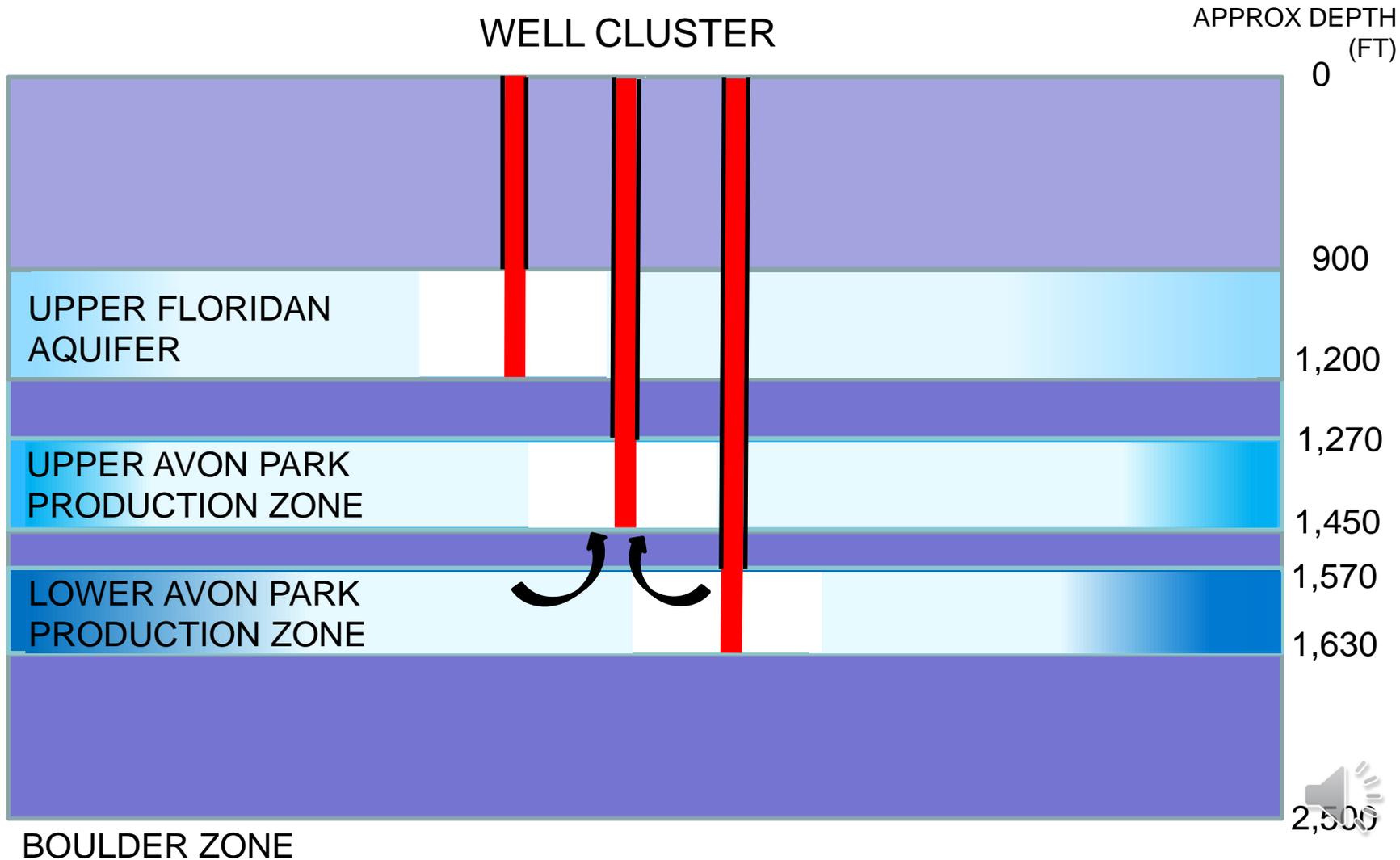


ASR WELLFIELD CONCEPTUAL DESIGN: STACKING

- Stacking water vertically in two or more aquifers at the same location can be cost-effective
- Separate intervals vs acidization
- Peace River, FL
 - Tampa Fm
 - Suwannee Fm
 - Avon Park Fm (potential)
- Hampton Roads VA
 - Upper Potomac
 - Middle Potomac
 - Lower Potomac
 - Differences in hydraulics, water quality, geochemistry
- Harris Galveston Subsidence District, TX
 - Five separate, potential storage intervals stacked 2,000 ft vertically



“Stacking:” ASR Proposed Conceptual Design at Lake Okeechobee, Florida



Orangeburg SC ASR Wellhouse – Two Stacked ASR Wells



Orangeburg S.C. ASR

ASR Wells



Monitor Wells

- 25 MGD Surface Water Treatment Plant
- Water Source – North Fork Edisto River
- Average Day Demand about 10 MGD
- Maximum Day Demand about 15 MGD
- Minimum Day Demand about 4 MGD
- ASR Recovery Capacity 6.5 MGD



Orangeburg SC SCADA Screen



Two Aquifers

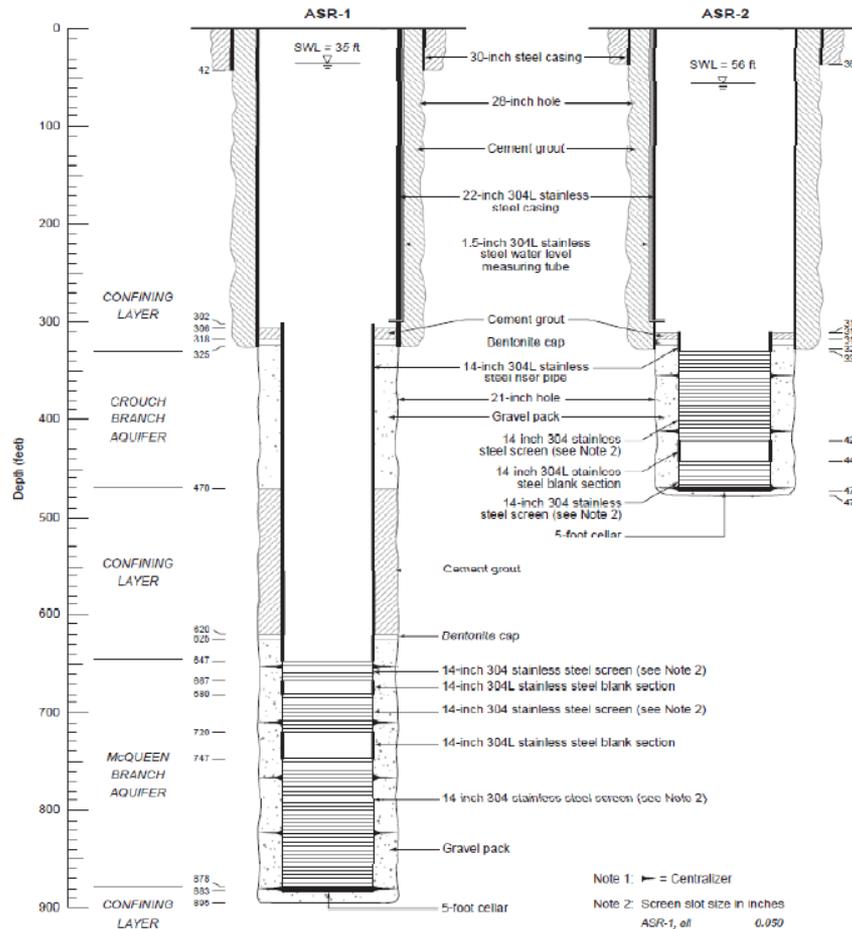
Two ASR Wells

Separation
Distance – 40 ft

Combined Design
Yield – 6.5 MGD



Orangeburg ASR Well Construction



Orangeburg Department of Public Utilities
Orangeburg, South Carolina
Aquifer Storage Recovery Program

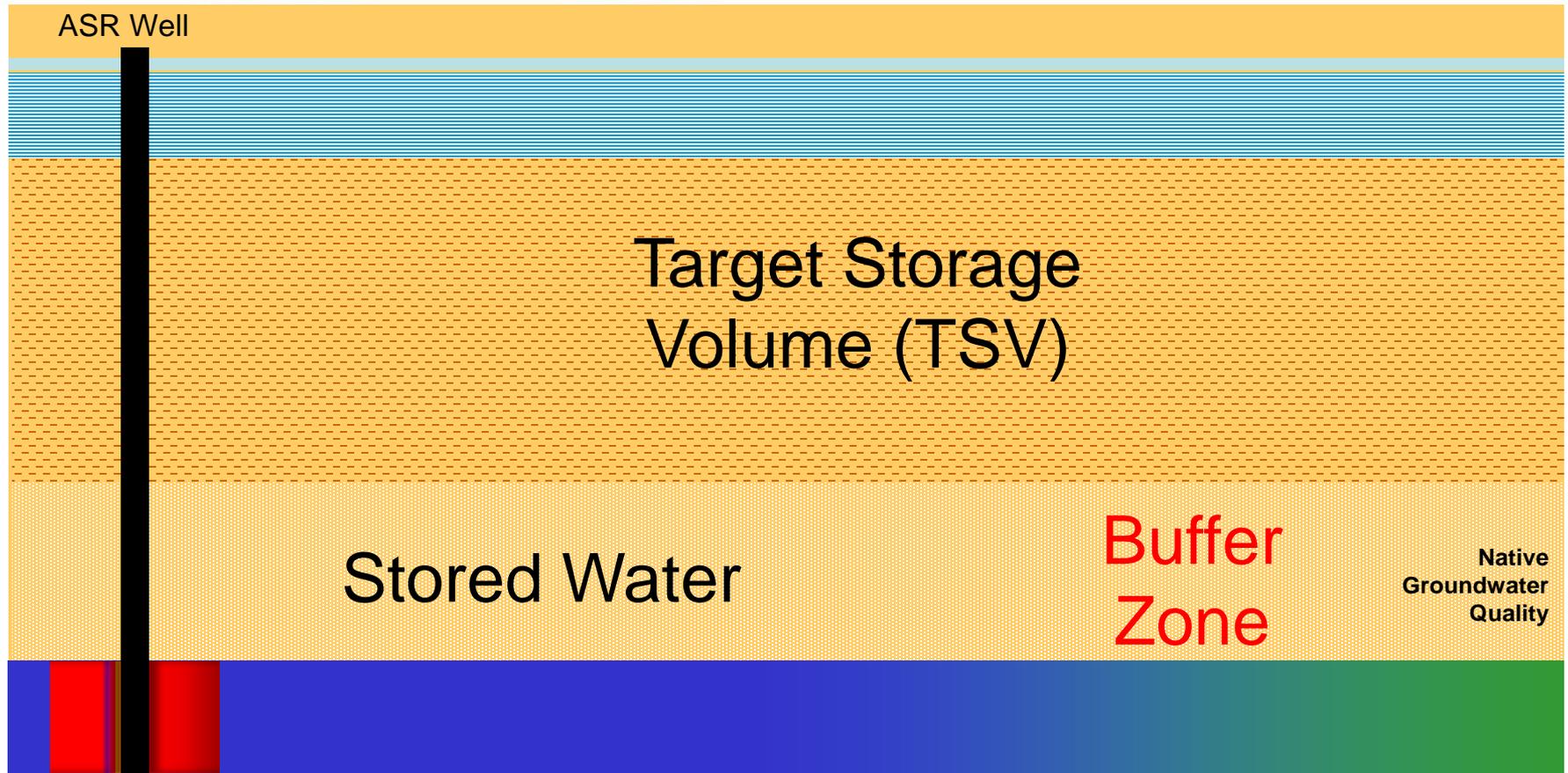
ASR Wells at the Water Treatment Plant
Well Construction Diagram—As-Built
September 2008



- 22-inch SS304 inner casings to about 330 feet
- 14-inch SS304 screens
 - ASR-1 647 to 878 ft
 - ASR-2 330 to 473 ft
- Two 6-inch PVC storage zone monitor wells with similar SS304 screens and settings, equipped with Insitu transducers
 - water level
 - conductivity
 - temperature
 - dissolved oxygen
 - redox potential
 - pH



Formation and Maintenance of a Target Storage Volume usually achieves recovered water quality goals



TSV is the sum of the stored water volume and the buffer zone volume. It is expressed in MG/MGD of recovery capacity, or in “days”



Factors Determining the Target Storage Volume (TSV)

- Hydrology
 - Recovered storage volume required
 - Buffer zone volume estimate
 - Duration of storage
 - Potential for losses due to density stratification and/or lateral movement
- Hydrogeology
 - Aquifer thickness
 - Hydraulic characteristics
 - Transmissivity, leakance, porosity (primary and secondary), potential for internal flow
 - Dispersivity



The TSV concept was developed to expedite achieving high recovery efficiency for ASR wells in brackish aquifers

- Historic approach to ASR well development
 - Multiple cycles over several years at approximately equal volumes
 - Leave a portion of the stored water underground during each cycle, building the “walls” of the “tank”
 - Slowly develop this buffer zone, increasing recovery efficiency with successive cycles
- Newer, better approach
 - Estimate and form the TSV, then conduct ASR cycles to confirm performance. Adjust TSV as necessary.
 - Less time, less cost
 - Demonstrated performance at several sites
 - Usually a one-time activity, not repeated unless demand increases for recovery of stored water



Forming and Maintaining the Buffer Zone is one of the keys to ASR Success

- Once the buffer zone volume has been formed, subsequent recovery efficiency should be close to 100%.
- It is measured in terms of “MG/MGD of recovery capacity,” or “days.” Typical values are 50 to 350 days, depending primarily on anticipated recovery duration, hydrogeology, water quality.
- Once formed, the buffer zone should not be recovered since it risks causing a substantial deterioration in recovered water quality.
- The buffer zone is best formed upfront, prior to cycle testing, as the last step in ASR well construction. The cost of the water may be capitalized. It can also be formed over the course of several ASR cycles, during each of which up to the same volume stored is recovered. This approach is much more time-consuming and expensive.



Estimating the Buffer Zone Volume

- Initial “placeholder” estimate is that the buffer zone volume equals the volume required for recovery, ie: $\text{buffer zone volume} = 50\% \text{ of TSV}$
 - Based primarily upon experience with ASR storage in brackish limestone, confined aquifers
- Adjust this percentage based upon operational and local experience
 - 30% may be appropriate for ASR storage in fresh, unconsolidated, confined aquifers
 - Most ASR storage aquifers have at least one water quality constituent not wanted in the recovered water
- Cost of buffer zone water volume is usually low and “one time.” Possible source from another, less-brackish aquifer
- **The TSV/Buffer zone approach may not work for ASR storage in high leakance aquifers overlain and/or underlain by aquifers containing brackish or poor water quality. Different approach may be required (HDD ASR well, “Freshkeeper” approach)**



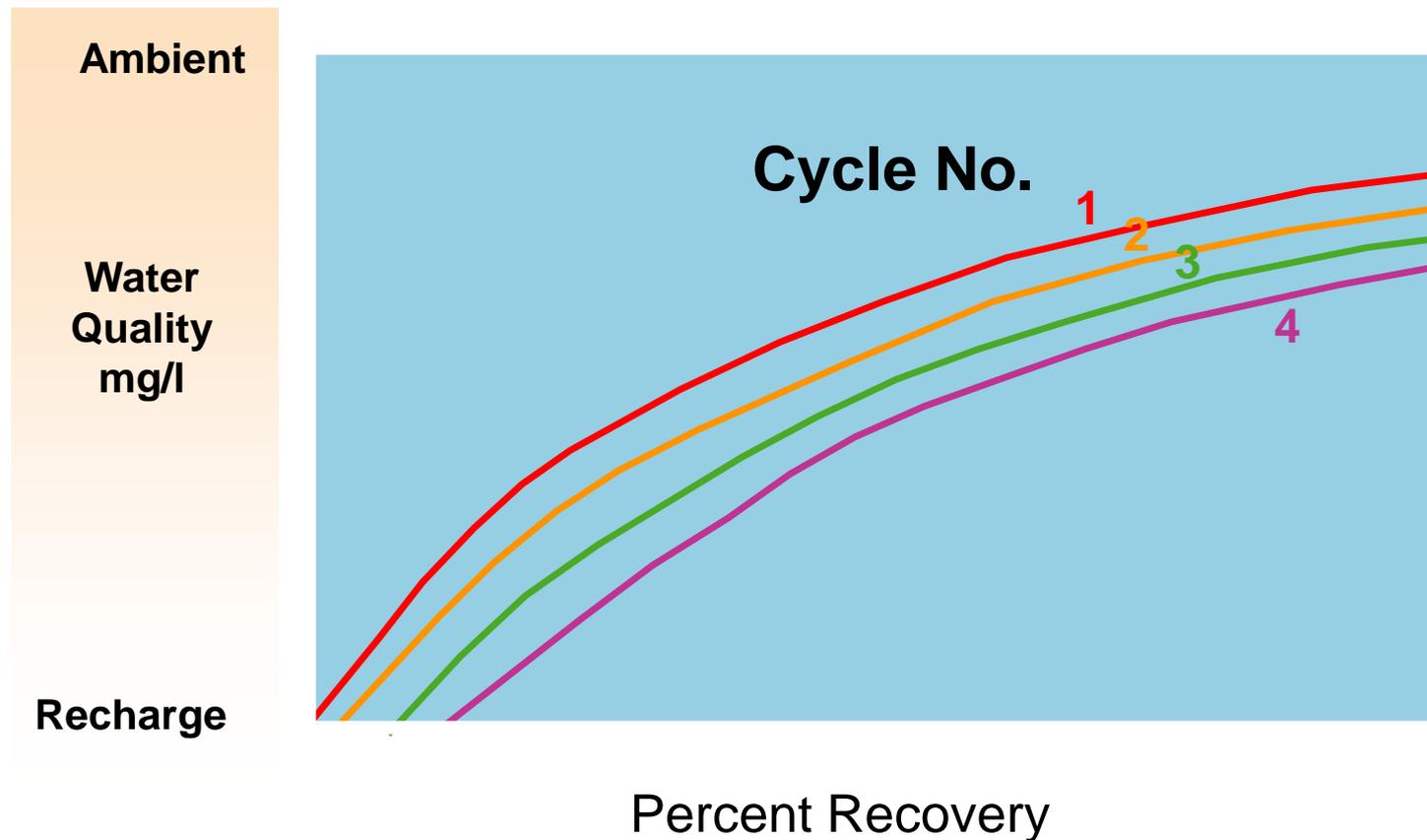
Manatee County, Florida 1983 Well ASR-1



ACEC Grand Award, 1984



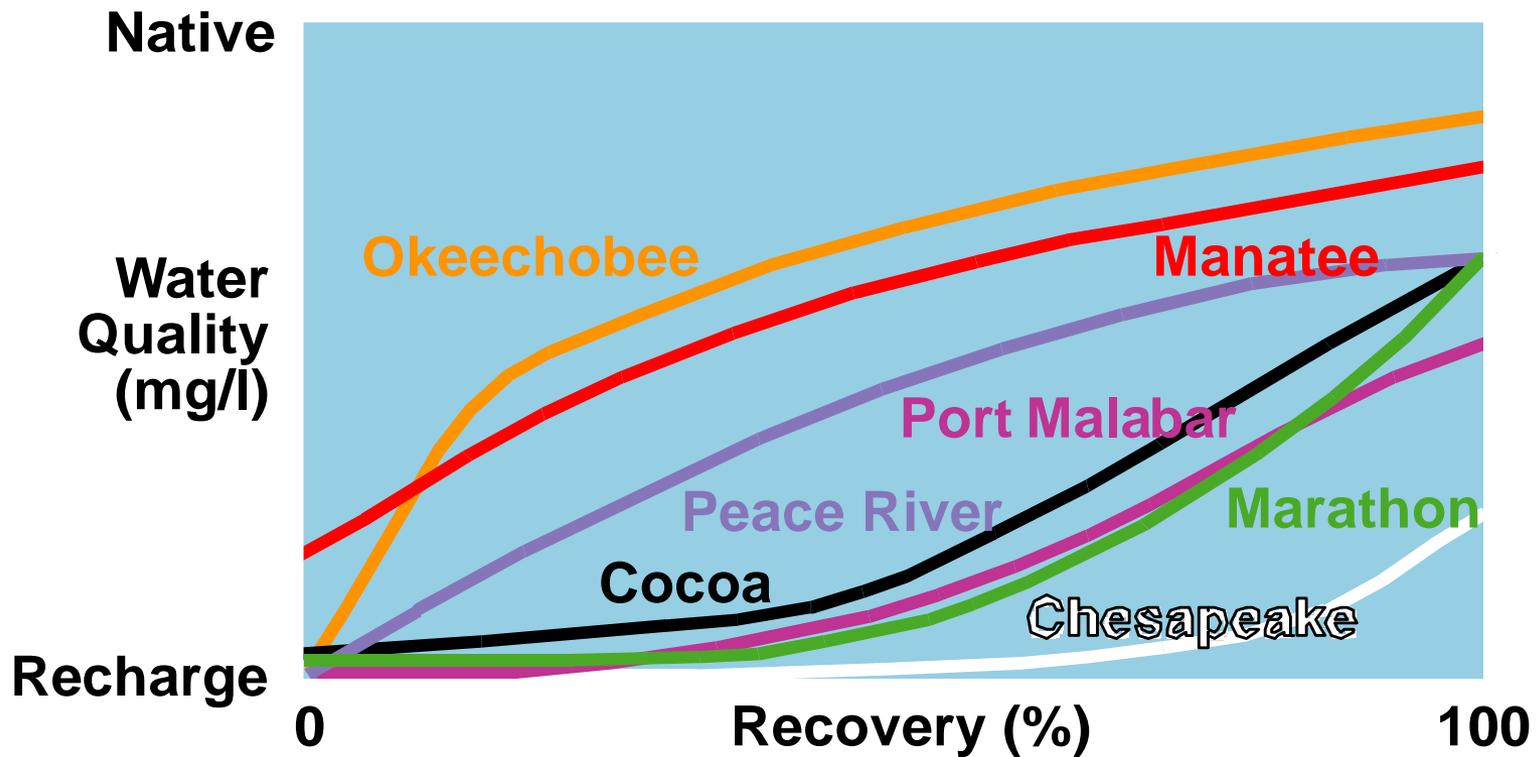
Water Quality Improvement in Successive Cycles



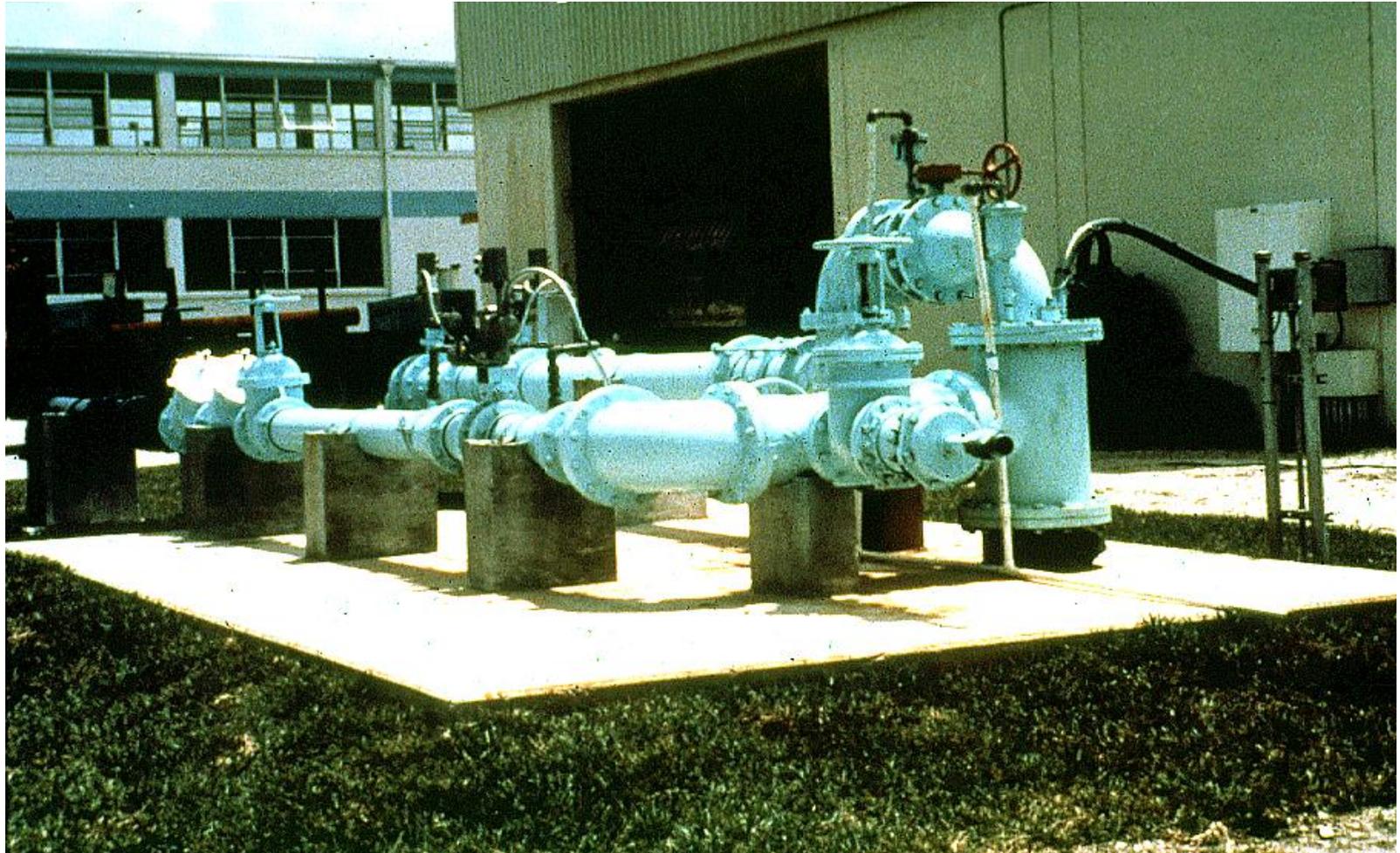
(based on Manatee County ASR experience, 1978 to 1983)



Water Quality During Initial Cycle Recovery

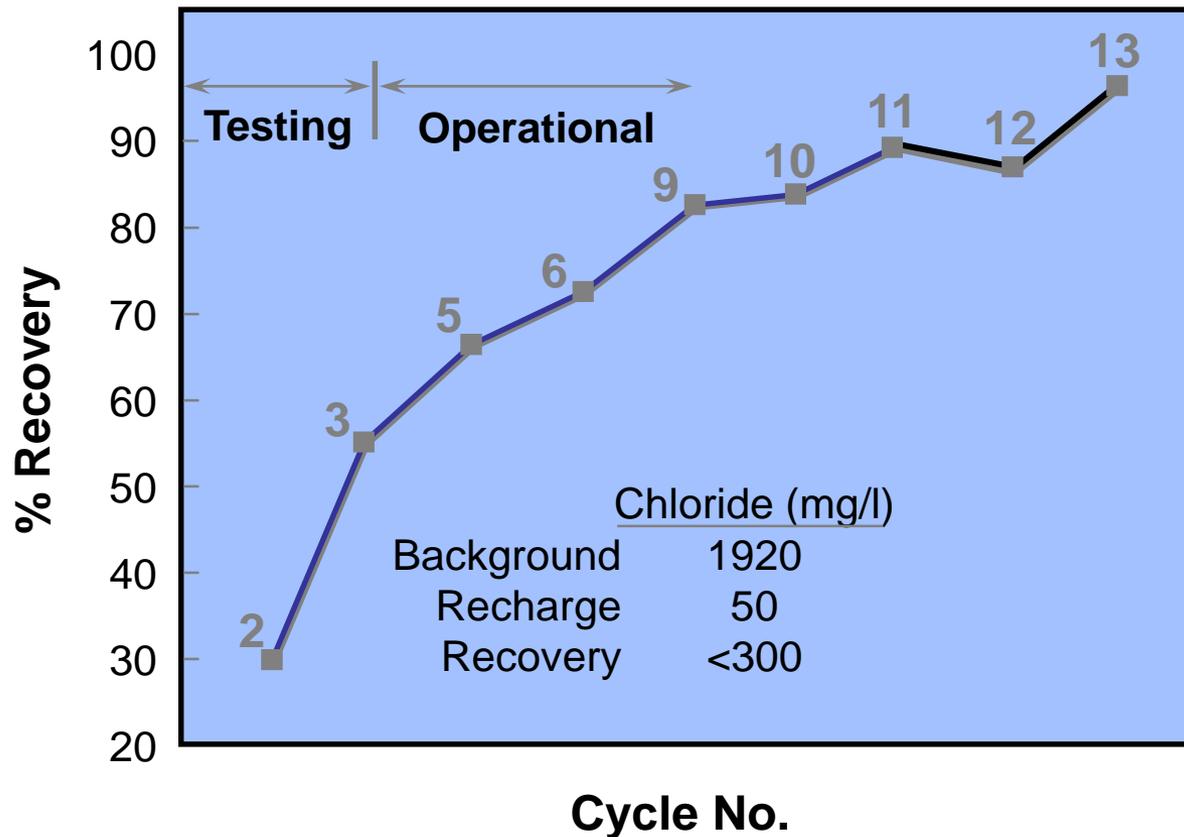


Boynton Beach, Florida, ASR Well



Boynton Beach ASR Well

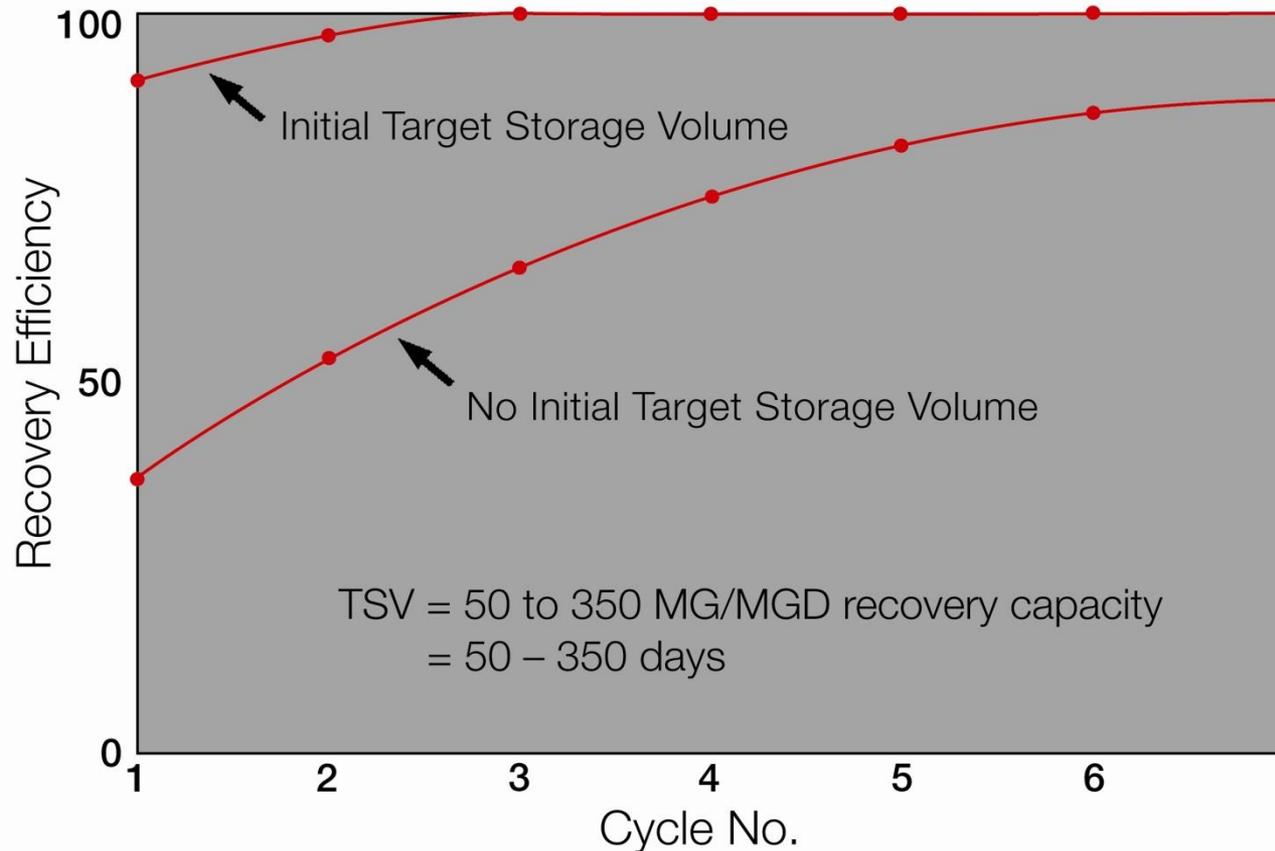
Percent Recovery by Cycle, 1993 to 1996



Each cycle approximately 40 to 60 MG stored and recovered



Initial development of the TSV facilitates achieving high recovery efficiency



Definition of Recovery Efficiency...

Do Not Count the Molecules!

Recovery Efficiency

- The volume recovered as a percentage of the volume stored in each cycle, meeting water quality criteria
- Typically close to 100% after a few cycles of equal volume
- Relies upon formation of a buffer zone around each ASR well

Recoverability

- Do we recover the volume that we need, at an acceptable rate and quality, at reasonable cost?
- No measurement units
- Less than 100% recovery efficiency may be just fine at many sites.



Most ASR sites achieve close to 100% recovery efficiency after the storage zone is fully developed (ie: buffer zone formed)

Site	Operating Since	TDS	% Recovery Efficiency
Manatee	1983	440	100
Peace River	1985	800	100
Cocoa	1987	1500	100
Palm Bay	1989	1320	100
Boynton	1993	4000	99
Marathon		37,000	40-70

Losses in recovery efficiency may be due to density stratification and/or local or regional lateral movement of water in the storage aquifer



Buffer Zone Options

- Form and maintain the buffer zone with the same, high quality water being stored for recovery (up-front or multiple cycles)
- Form and maintain most of the buffer zone with water from a different source of intermediate quality that may be seasonally available and cost-effective
- Interim recharge with temporary facilities between end of well construction/testing and equipping of the well, typically 6 to 8 months



Interim recharge allows formation of all or part of the buffer zone, and of the TSV, prior to starting ASR operations

- Upon completion of well construction and testing, and while equipping the ASR well:
 - Obtain baseline water quality samples (wells, recharge water) and water levels
 - Provide temporary wellhead piping, flowmeter, valves, sampling taps, pressure gages, etc. Disinfect well and wellhead piping
 - Begin interim recharge, monitoring mounding and clogging (no pump yet available for backflushing)
 - Continue during construction of wellhead facilities, usually for several (6 to 8) months
 - Monitor flows, volumes, water levels, water quality at ASR well and any monitor wells. Estimate porosity, based on MW response
 - Consider water column density changes affecting water levels
- Start cycle testing and ASR operations



Well Clogging and Redevelopment

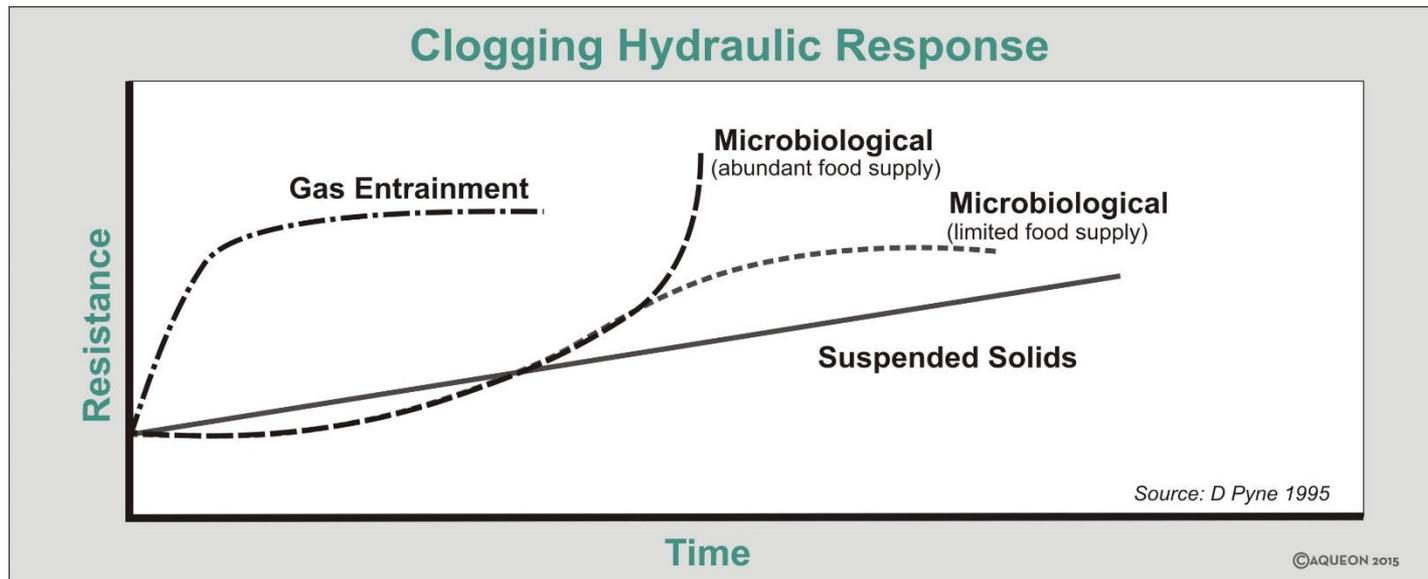
- Source water characterization
- Well clogging relationships
- Redevelopment frequency
- Recharge and recovery flow rate trends & Sp.Capacity
- Pretreatment options



$SC_i < SC_p$
SC injection < SC production
“Balloon Effect?”



Well Clogging Relationships



ASR well clogging has several causes:

- Clogging of ASR wells storing treated drinking water has been caused by sand, rust, alum floc, live shrimp, dead mice, algae, twigs, branches, construction timber, albino slugs, an oil spray lubricant can, cement pipe lining, railroad tie, baby doll's head, etc.
- Also due to geochemical plugging, air-binding, bacterial reactions, and inappropriate materials of construction.
- Periodic backflushing of ASR wells is a key to success, along with keeping these solids out of the recharge water



The Problem of Air Entrainment During Recharge of ASR Well

Downhole Velocity
 $V < 1$ ft/sec

No Problem

If downward velocity is less than about 1 ft/sec the air bubbles will rise to the top and be vented from the well.



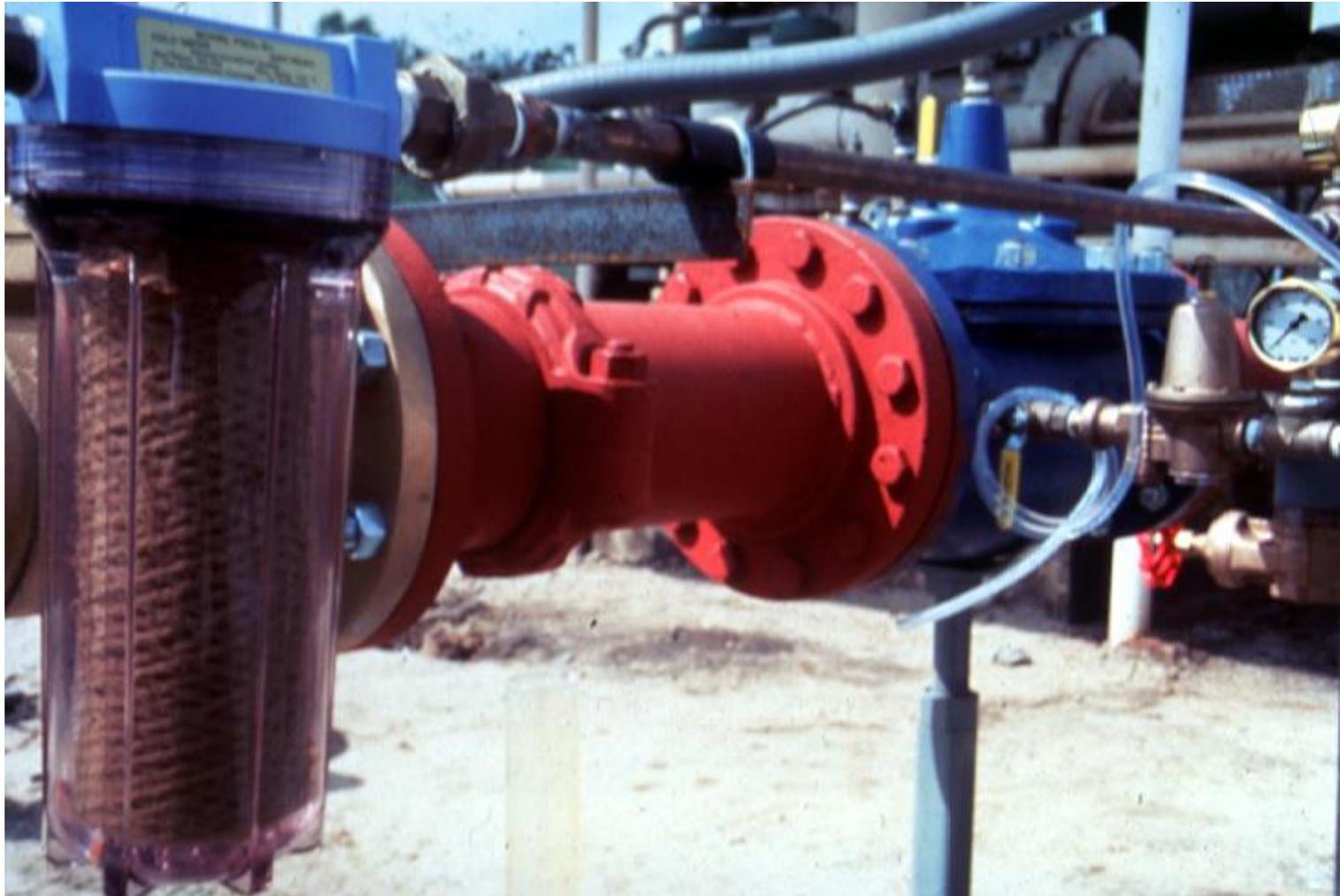
Downhole Velocity
 $V > 1$ ft/sec

Air Entrainment Problem

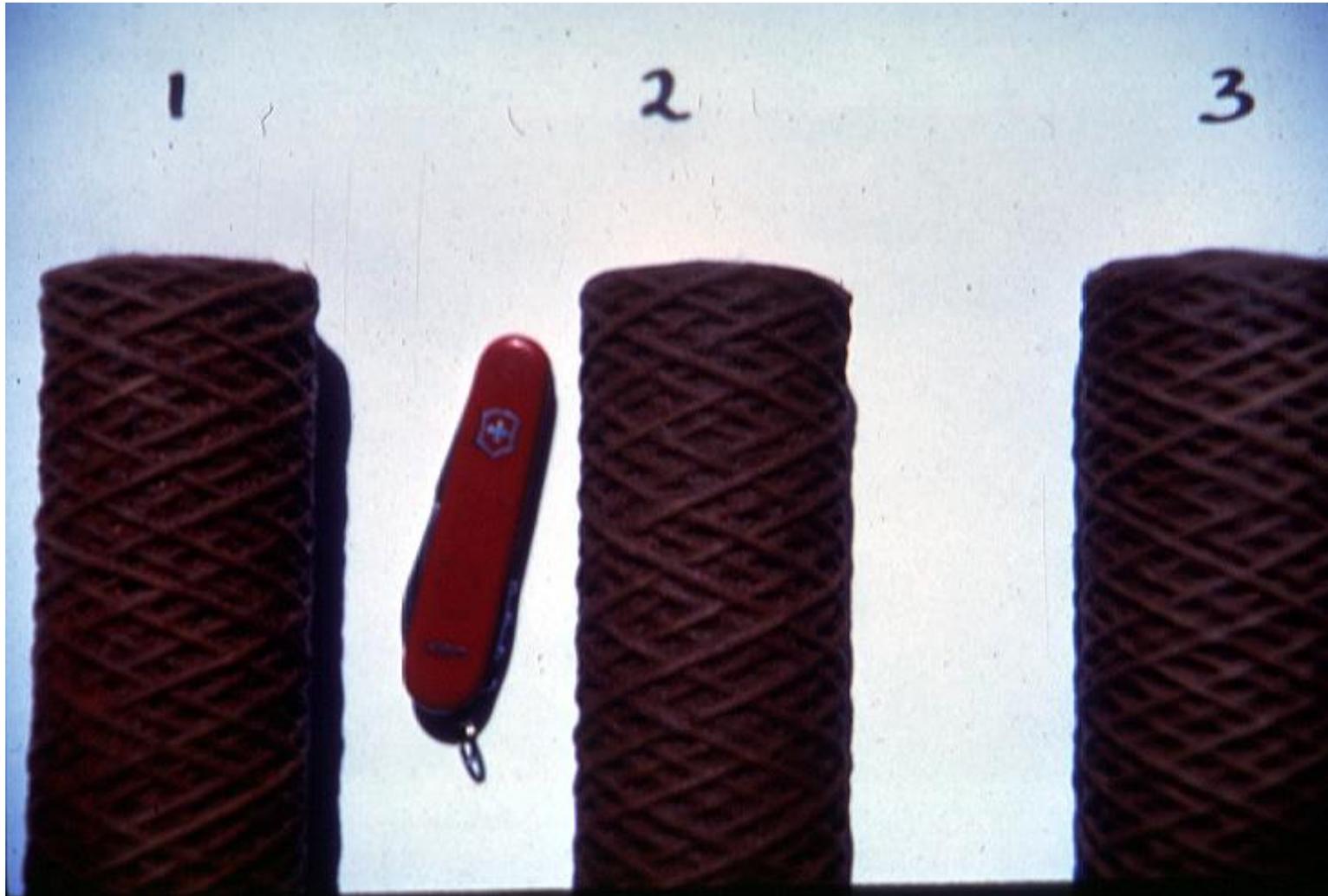
If downward velocity is more than about 1 ft/sec the air bubbles will be carried down the well casing and into the formation of the aquifer.



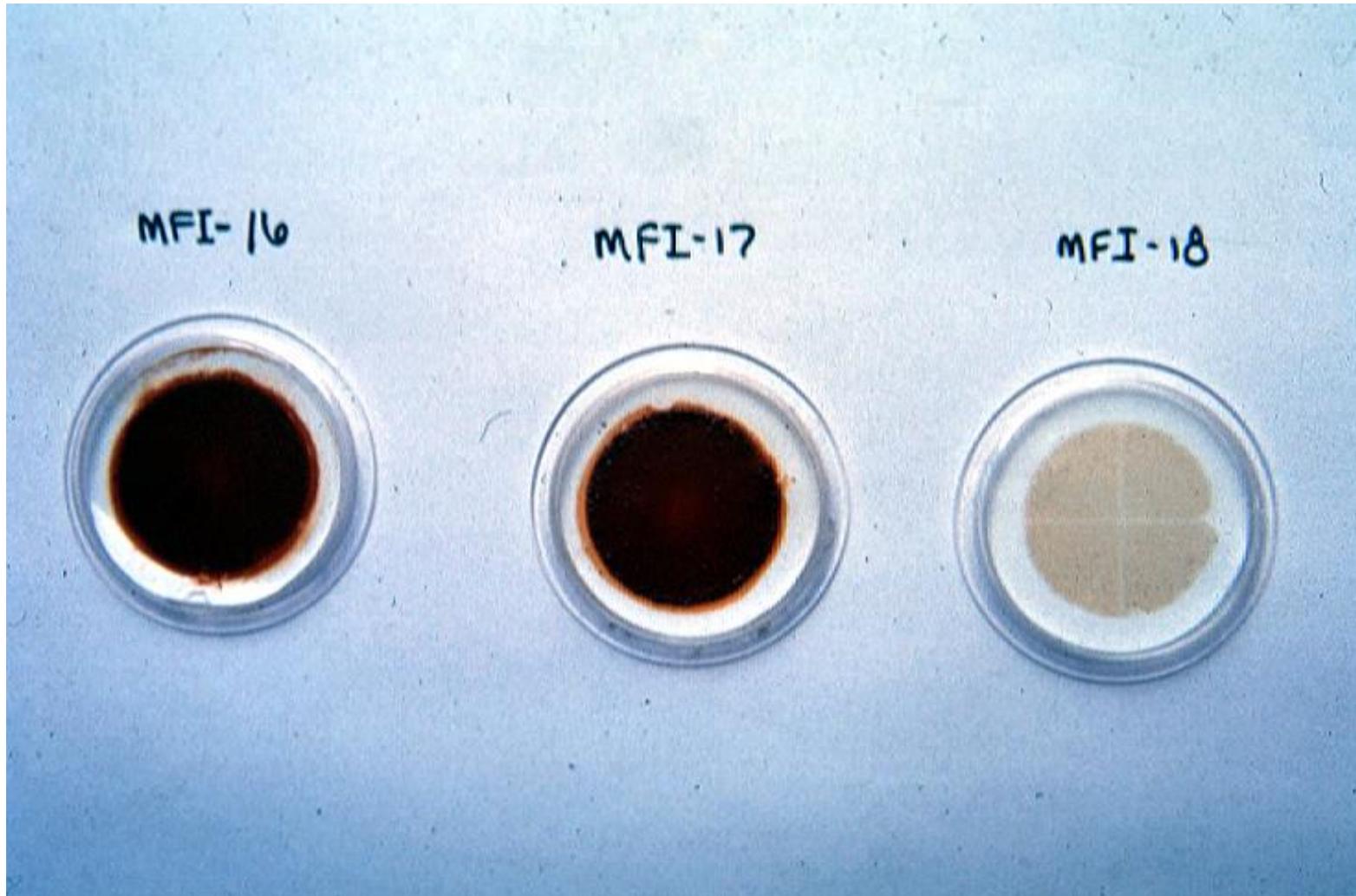
ASR Well Clogging



ASR Well Clogging



ASR Well Clogging



Clogging close to the well occurs in screened wells

- Rehabilitation needed every few days to every few years due to chemical precipitation; microbial growth in the screen, gravel pack and surrounding formation, air binding, and particulates in the recharge water
- Energy sources include nutrients and carbon in recharge water, sulfur and iron
- Same processes occur in open borehole wells but are less likely to cause clogging and the need for well rehabilitation
- Clay dispersion/ swelling



Arkal Spin-Klin Automatic Filtration System

- Filter Down To 25 microns
- Used widely in agricultural sector



Pressure Filters



Well Redevelopment

- Flush wellhead piping and well to waste prior to recharge and at beginning of recovery for a few minutes to an hour.
- Periodically backflush well to waste for a few minutes to an hour during recharge periods to remove accumulated solids. Multiple backflushes may be needed.
- Typical backflush frequency is every few weeks to months. Sometimes every few days. Sometimes not required, other than at beginning of recovery.
- Use same pump for backflush and recovery. Soft start vs hard start
- Radial Injection Surge Development (RISD) approach to enhanced well productivity



Backflushing Frequencies at Selected Operational ASR Sites

Site	Backflushing Frequency	Lithology
Wildwood, New Jersey	Daily	Clayey Sand
Gordons River, New Jersey	Daily	Clayey Sand
Peace River, Florida	Seasonal	Limestone
Cocoa, Florida	Seasonal	Limestone
Palm Bay, Florida	Monthly	Limestone
Las Vegas, Nevada	Seasonal	Alluvium
Chesapeake, Virginia	Twice-Monthly	Sand
Seattle, Washington	Weekly	Glacial Drift
Calleguas, California	Monthly (approx.)	Sand
Highlands Ranch, Colorado	Monthly	Sandstone



Mechanical measures to restore clogged wells

- Back flushing (pumping)
- Intermittent pumping
- Juttering
- Over pumping
- Surging
- Sectional pumping
- Vacuum
- Under reaming
- Ramping up & down of submersible pumps
- Sonic jetting
- Incremental pack redevelopment
- High pressure jetting
- Air jetting
- Hydrodynamic fracturing
- Scraping blades and removal of previously injected muddy water
- Dry ice
- Brushing (wire and rotary)
- High frequency vibration



Clogging Will Happen. Clogging Can Be Managed

- To recognise the potential for clogging and mitigate, through engineering design and through operational management practices requires:
 - continual monitoring and assessment of hydraulic performance
 - specialist knowledge and skills to remediate the clogging.
- Remediation methods to address clogging are very site specific and what works in one hydrogeological setting may not always be successful in another location.
- Remediation approaches may differ between different wells within the same wellfield.

Reference: Clogging issues associated with managed aquifer recharge methods: Russell Martin
downloadable from <http://recharge.iah.org/recharge/clogging.htm>



Water must be treated before ASR storage to...

- Prevent aquifer clogging through biofouling, physical or geochemical reactions.
- Meet regulatory requirements protecting ground water quality.

***West Palm Beach, Florida
Largest ASR Well, 8 MGD***

Strainer plus Cl_2 for pretreatment



Treatment of recharge water may utilize a wide range of technologies.



*Beaufort-Jasper
Water & Sewer
Authority,
South Carolina*

- Strainers
- Filtration
 - sand (gravity, pressure)
 - ring, cartridge filters
 - **Bank filtration**
- Micro/ Ultrafiltration
- Desalination/ Reverse Osmosis
- Disinfection
 - chlorine
 - chloramine
 - chlorine dioxide
 - ozone
 - UV treatment
 - Advanced oxidation
- Air stripping
- Chemical treatment



Combining bank filtration and UV disinfection can enhance ASR recharge water quality, but at higher cost.

- Bank filtration typically achieves 3 to 5 log cycle removal of pathogens, depending upon travel time.
- UV disinfection would probably be designed to achieve 3 log cycle attenuation of pathogens.
- Expected pathogen concentration in source water would be 1 to 3 log cycles.
- Pathogen attenuation typically occurs naturally in a few days of aquifer storage, per log cycle
- Reduced oxidation-reduction potential of ASR recharge water may reduce tendency for any subsurface geochemical reactions.
- A “compliance zone” for measurement of water quality relative to standards is helpful for achieving standards.

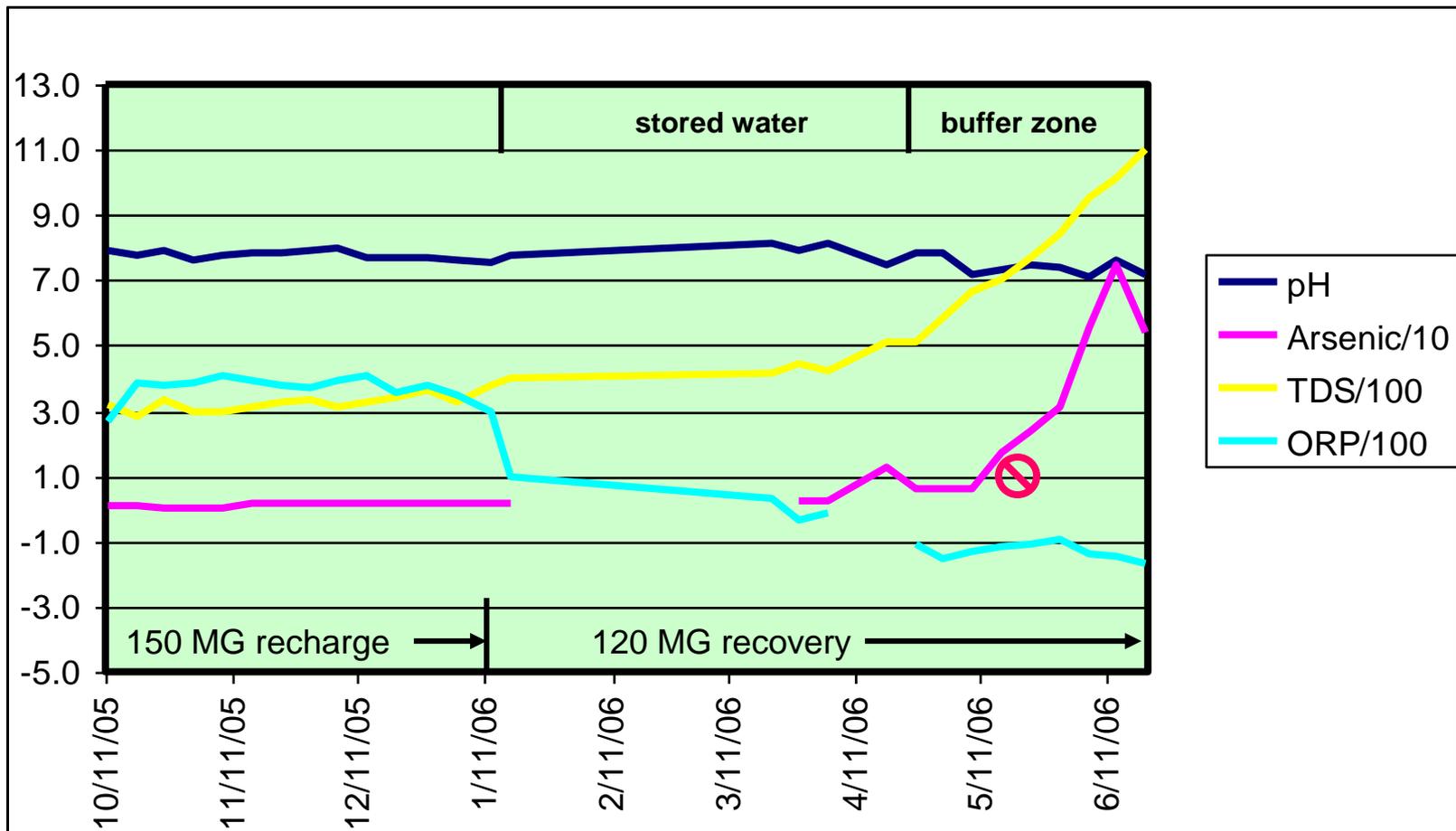


We can adapt the TSV and buffer zone concept to the attenuation of arsenic and perhaps some other metals

- Complex interplay of physical, geochemical and microbial processes determine As concentration, plus the conservative mixing process
- What buffer zone volume would be required in order to ensure that arsenic is not recovered from the ASR well?
- As moves as a “rolling front,” mobilizing when oxygen is available and adsorbing and/or precipitating when oxygen is no longer available
- Consider data from several ASR wellfields in Florida
- Possible extension to other states, other metals?



Bradenton, Florida ASR Cycle 6

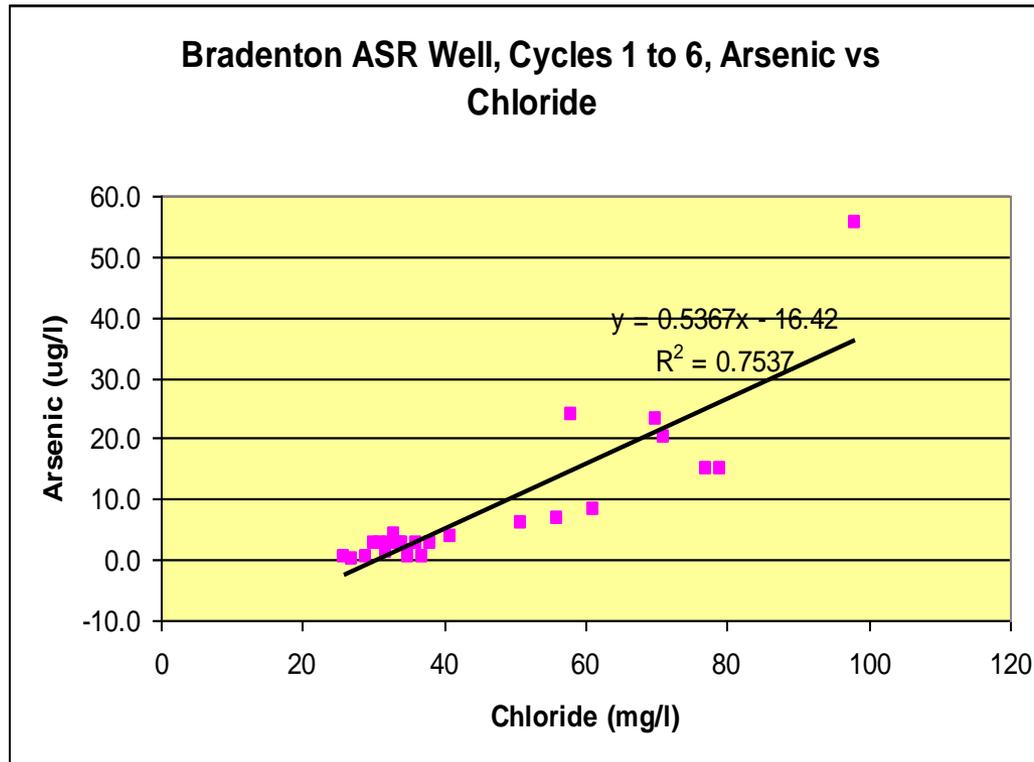


Target Storage Volume (TSV)

- TSV = 50 to 350 MG/MGD of recovery capacity, or “days”
- TSV < 70 days associated with elevated As
- TSV > 70 days associated with acceptable As concentrations
- This is a “Rule of Thumb,” based on Florida experience
- TSV depends upon hydrogeologic factors and also storage volume required. It is scale-dependent.
- As reactions are complex. Sources of As are varied



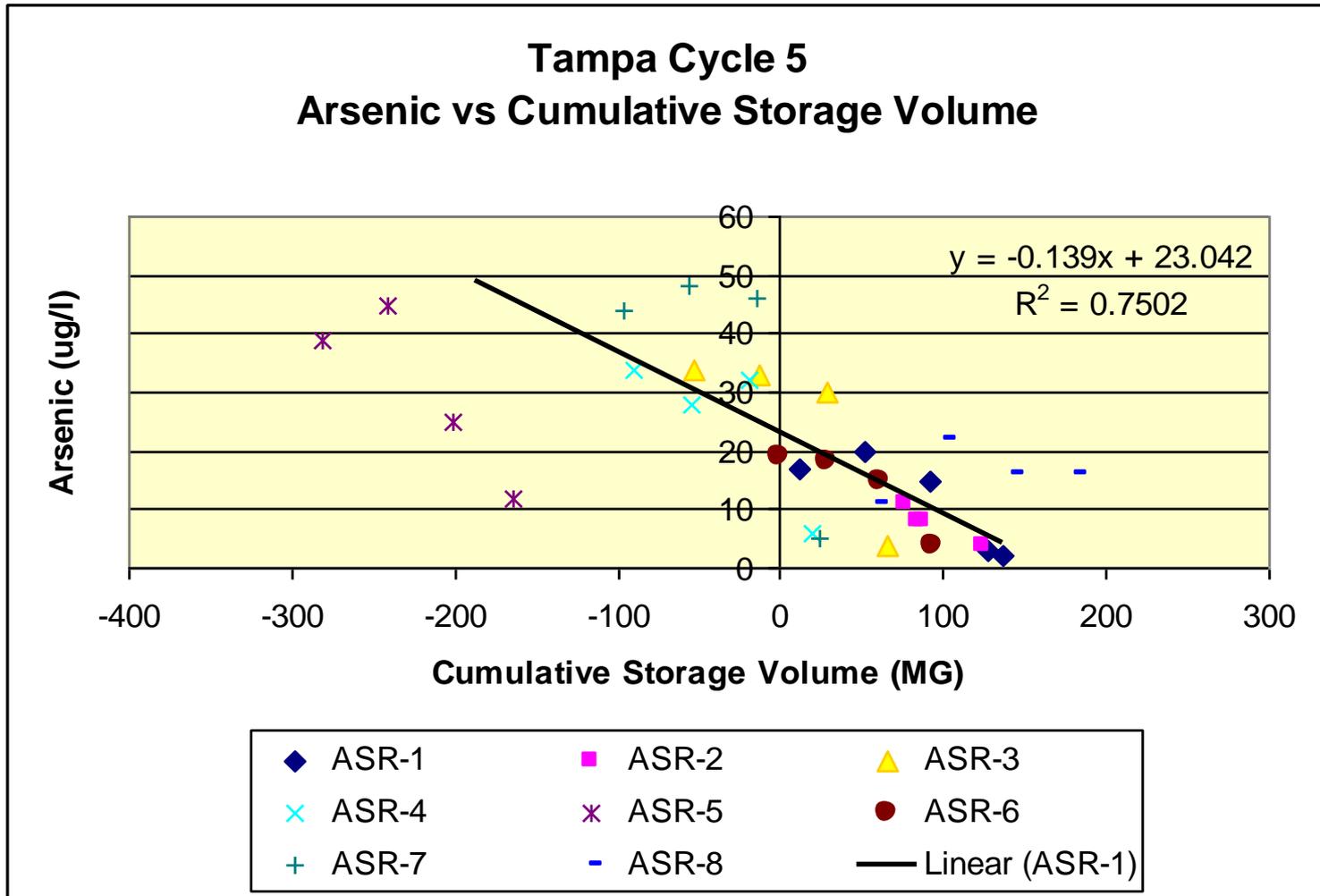
The best correlation achieved at Bradenton was a relationship between [As] at the ASR well and Chloride



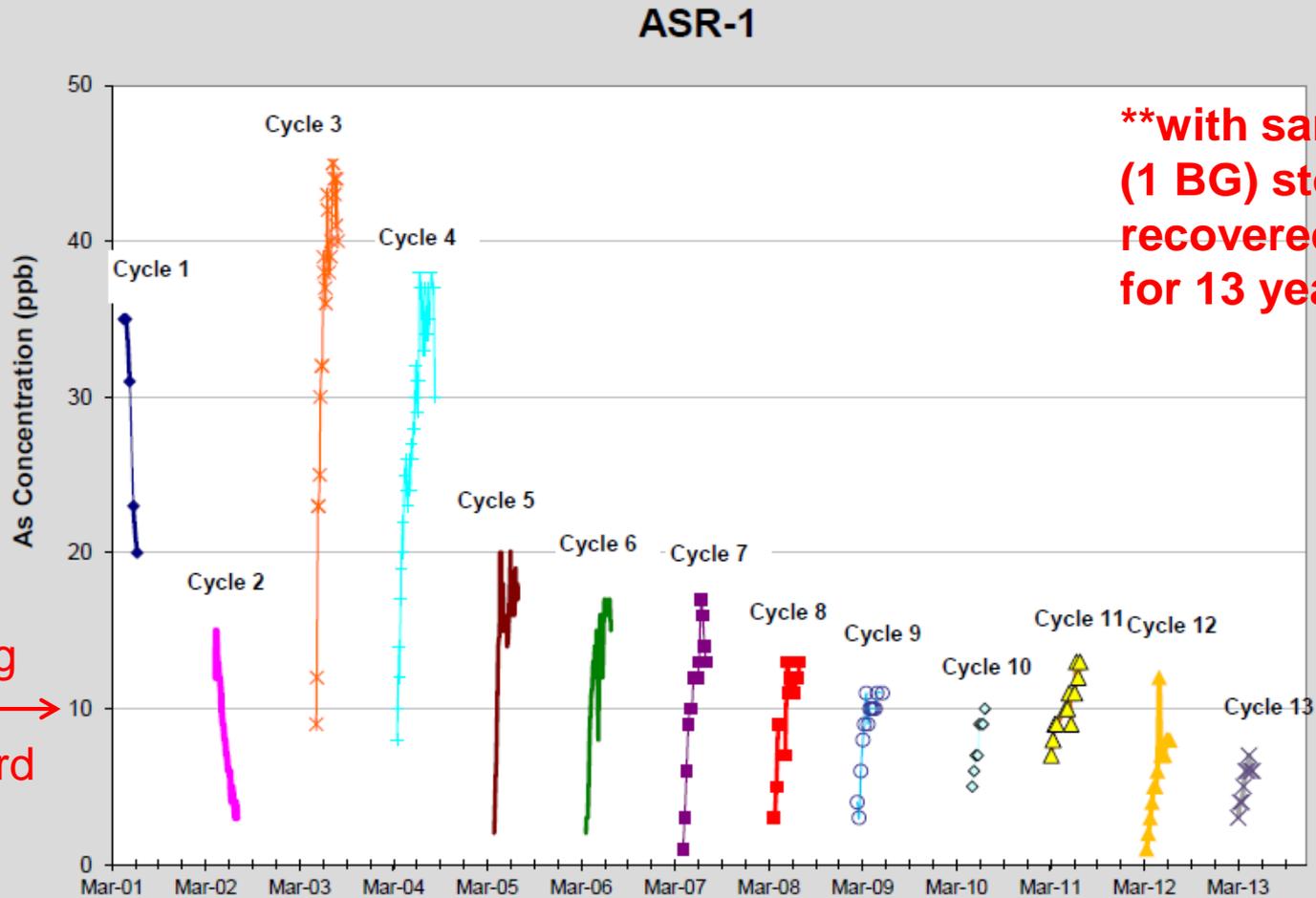
Consider the potential use of Chloride or TDS as an operational surrogate for Arsenic



Arsenic declines as the cumulative storage volume increases



Recovered water quality usually improves with multiple cycles**



**with same volume (1 BG) stored and recovered each year for 13 years

City of Tampa, Florida



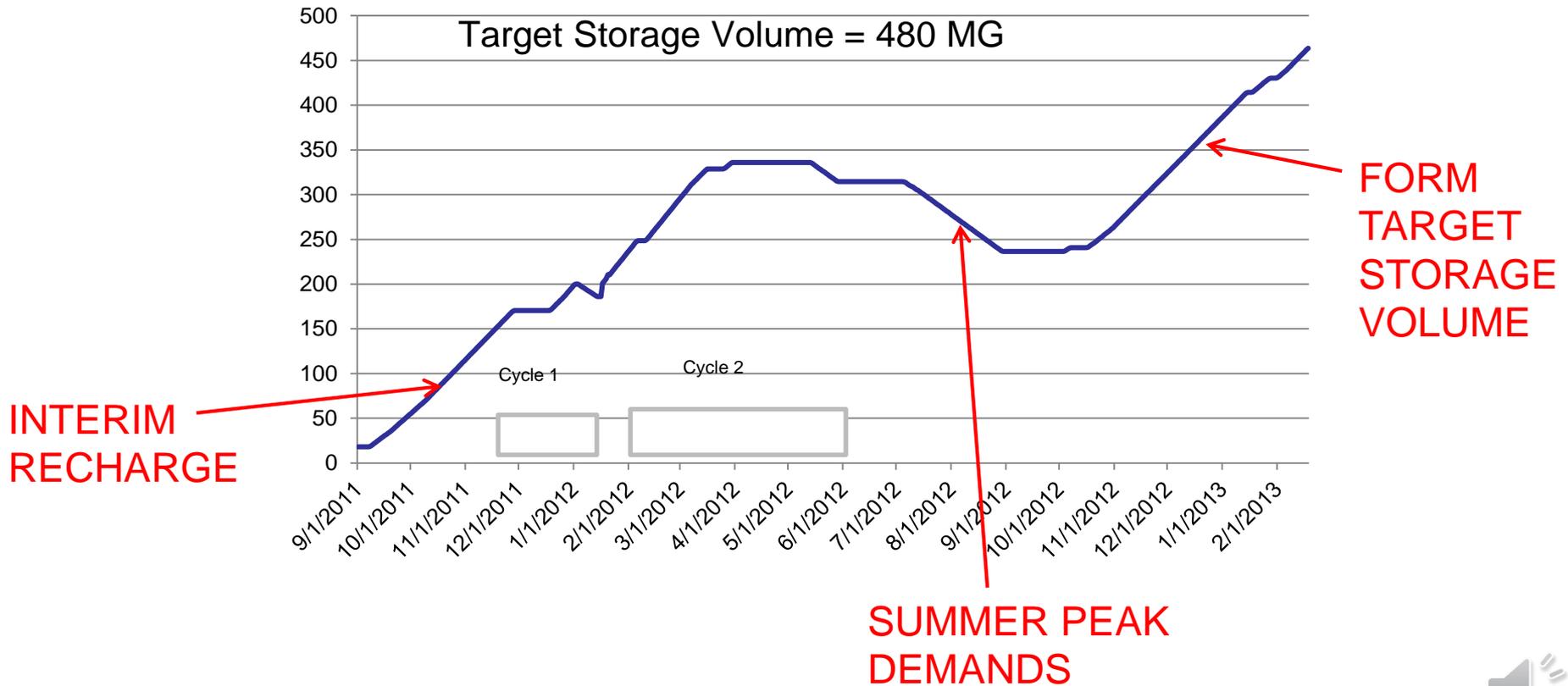
Cycle Testing

- Each cycle includes a recharge period, storage period and recovery period, with data collection
- Number and design of cycles depends on the technical and regulatory issues of greatest concern
 - Disinfection byproduct attenuation; geochemical reactions; clogging/mounding/backflushing frequency; dispersion; recovery efficiency; nutrient/TOC reduction, lateral movement of stored water, etc.
- Superimpose cycle testing on normal operations to steadily build the Target Storage Volume. Do not fully recover, or over-recover, during each cycle.
- Typically 2 to 3 cycles, within range of 1 to 8



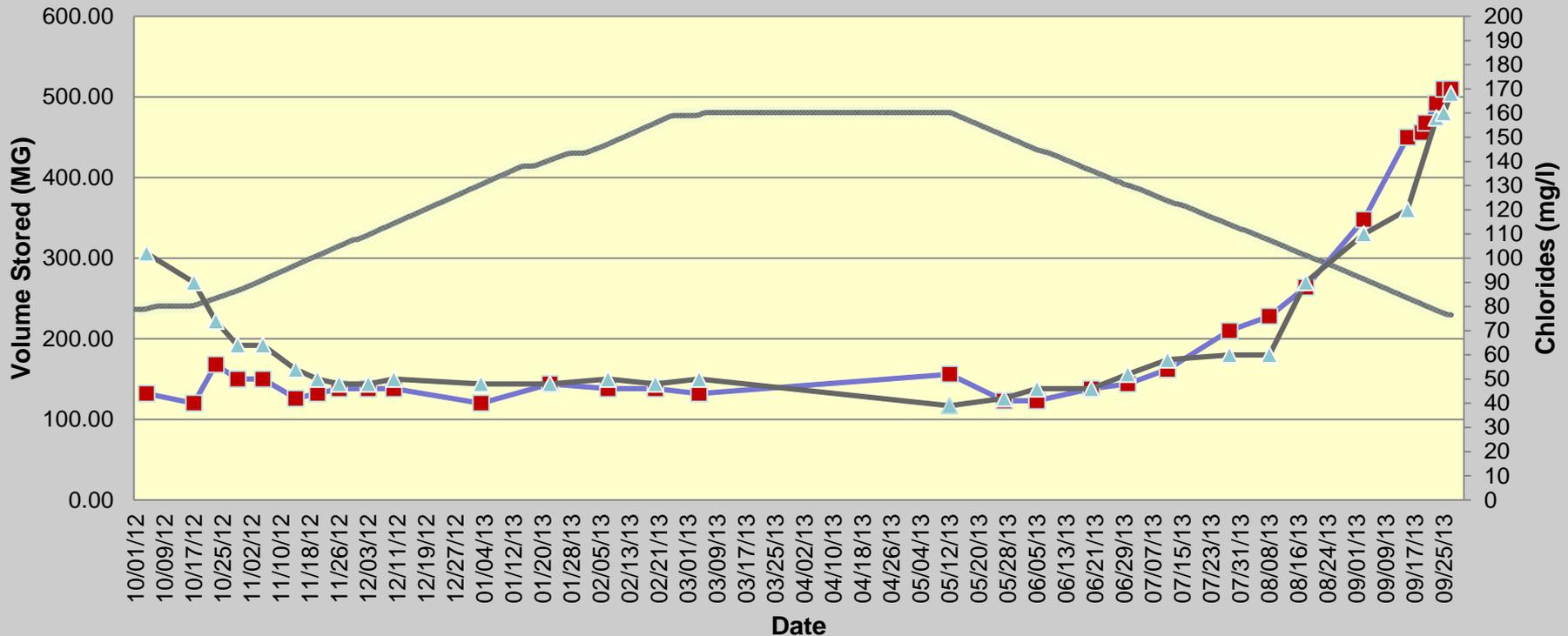
Hilton Head, South Carolina Cycle Testing Program

Cumulative Volume, MG

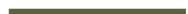


Stress Test Results: ASR goals achieved and exceeded

HHPSD ASR-1 Well Performance



250 MG Recovered
Chloride < 170 mg/l

-  Cumulative Volume Stored (MG)
-  Chloride at ASR Well (mg/l)
-  Chloride at MFA Monitor Well (mg/l)



San Antonio Water System, Texas

- Twin Oaks WTP and ASR wellfield is 30 miles south of San Antonio
- Wellfield area is 3,200 acres
- 29 ASR wells and 3 production wells
- 1,800 to 2,500 gpm/well
- Total recovery capacity – 60 mgd
- Third largest ASR wellfield in U.S.
- Carrizo-Wilcox is a semi-confined sand aquifer
- Began recharge in 2004; more than 100,000 AF stored to date
- Total construction cost: \$238M
ASR wellfield cost: \$52M
ASR unit capital cost:



SAWS ASR Wellfield, 2005

US\$0.87/gpd recovery capacity



San Antonio Water System (SAWS)

- ASR objectives are long term storage to meet the “Drought of Record” and providing emergency water supplies
- During the 2010-2011 extreme drought the SAWS ASR wellfield produced 40 mgd to augment local water supplies for several months, relieving pressure on groundwater withdrawals from the Edwards Aquifer which supplies Comal and San Marcos Springs, plus all local water supplies



SAWS Flow Control Facilities and Ground Storage Reservoir at Twin Oaks WTP and ASR Wellfield



San Antonio Water System ASR

- Water recovered from ASR wells normally does not require retreatment other than disinfection
- Water pumped from the three production wells requires full treatment for Fe and Mn removal, plus disinfection
- Toward the end of the drought ASR recovered water required treatment for Fe and Mn removal, due to blending with ambient groundwater from the three production wells



SAWS Twin Oaks Water
Treatment Plant at the ASR
Wellfield, 2006



SAWS ASR: Lessons Learned

- Successful performance during a recent extreme drought received enthusiastic local support and was noted by water managers statewide, galvanizing interest in ASR in Texas
- Mitigation plan has been effective for dealing with perceived offsite adverse impacts upon wells and groundwater levels
- An operating plan is needed to guide decisions regarding when to start and stop recharge and recovery; when is the “tank” full, etc.
- Governance issues were resolved in Texas, strengthening the rights of a landowner to recover water that he stores beneath property that he owns, leases or otherwise controls
- Legislation and rule-making has boosted ASR development in Texas by addressing governance constraints.



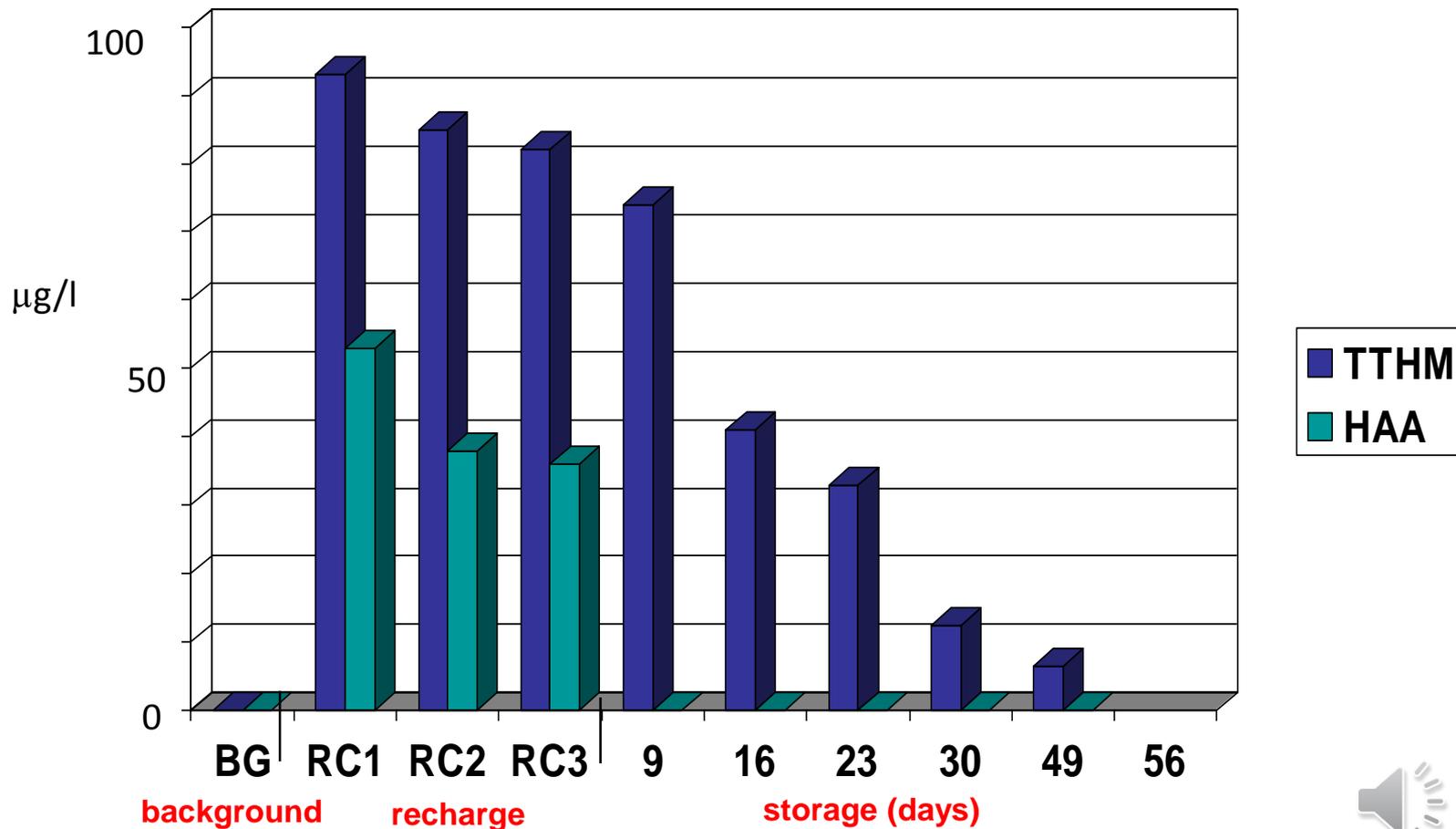
ASR Workshop Outline

Tuesday October 6, 08:00 to 12:00

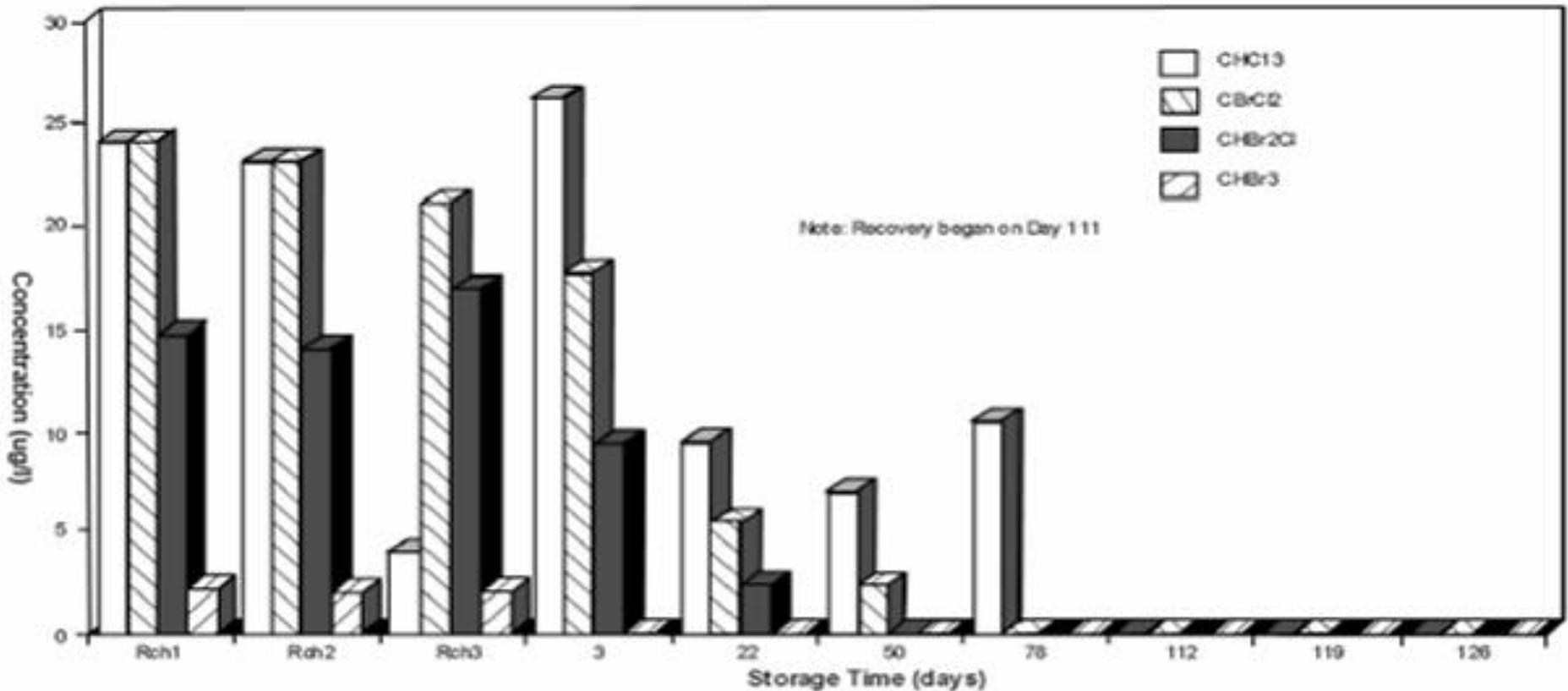
1. Introduction to Well Recharge/ASR
2. Phased Approach to Successful ASR
ASR Applications
Key Principles for Successful ASR
3. Science/ Technology
Design of ASR Wells and Wellhead Facilities
4. Well Conditioning and Operation of ASR Wells
and Wellhead Facilities
5. ASR Economics/ Regulatory (optional, time permitting)



Disinfection Byproduct Reduction: Centennial WSD, Denver, Colorado



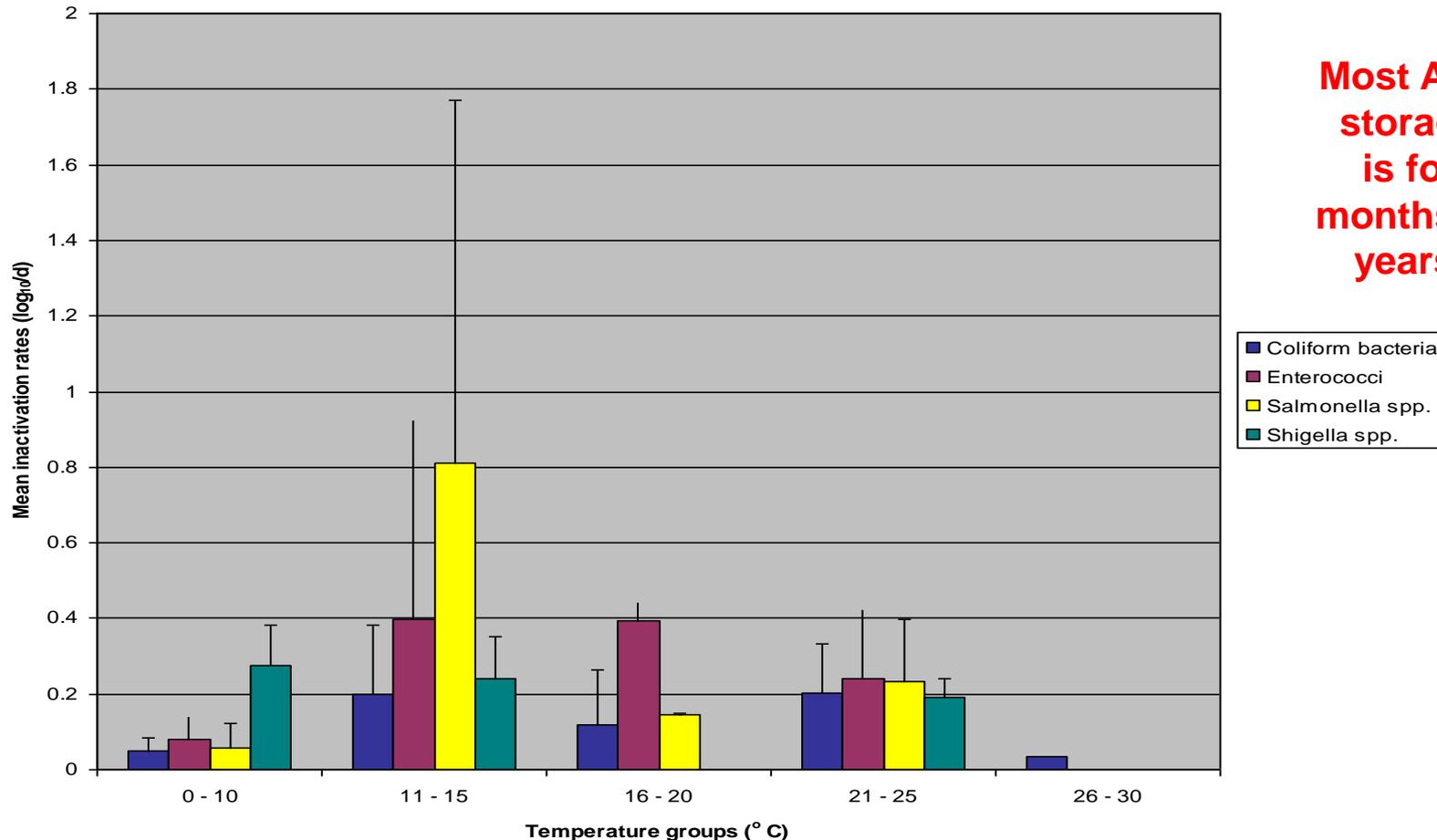
THM Constituents Attenuation Thames Water Utilities, England



Brominated TTHM species attenuate first; Chloroform attenuates last. Due to anaerobic microbial activity



Bacteria Mean Inactivation Rates in Temperature Groups



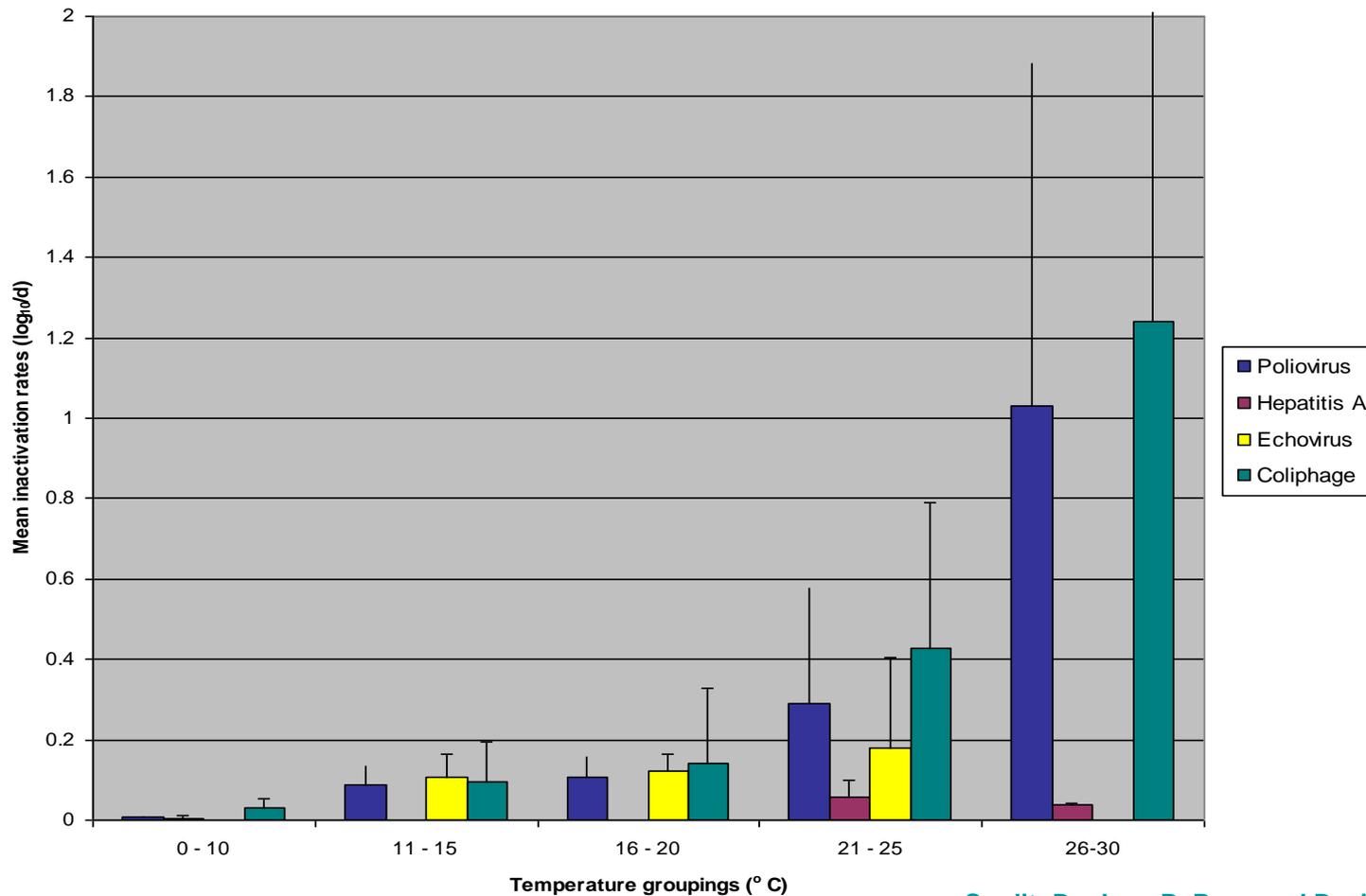
Most ASR storage is for months to years.

Error bars reflect standard deviation of rate values observed in each temperature group.

Credit: Dr. Joan B. Rose and David E. John, University of South Florida, 2002.



Virus Mean Inactivation Rates in Temperature Groups



Credit: Dr. Joan B. Rose and David E. John, University of South Florida, 2002.



Further research has been conducted regarding the fate of microbiota during ASR storage.

- Microbiota may be present during subsurface storage of seasonally-available, partially-treated surface water
- Objective was to provide a source of reliable, scientific, peer-reviewed data and information for consideration by environmental groups, regulators and other interested people
- Laboratory, field and literature investigations
 - Dr Joan B. Rose and Dr. David E. John/ U. of South Florida
 - Dr Simon Toze/ Australia
 - Dr John Lisle/ USGS/ Tampa
- ASR Systems LLC search of field investigations
- Project sponsored by SWFWMD and SFWMD
- Results posted on a website:

www.asrforum.com



Literature Search includes summaries and data from field investigations and experience.

Fate of Microbiota in

- ASR wells
 - Florida
 - Australia
- Drainage wells
- Sinkholes
- Observation wells for deep injection well systems
- Bank filtration



Kerrville Texas Well ASR-1



Microbiota concentrations attenuate during ASR storage.

- Bacteria, viruses attenuate typically in 1 to 30 days per log cycle.
- Principal mechanisms include temperature, salinity, native microbiota in the storage zone, and other factors.

Suggested Regulatory Policy: Evaluate compliance with drinking water standards in the aquifer at the edge of a compliance zone around the well



Microcontaminant attenuation during ASR storage – WRF Research

- Four Reclaimed ASR sites
- 27 samples during background, recharge, storage, recovery at each site
- 99 constituents analyzed
- Zero to two monitor wells per site
- Fresh to saline aquifers
- Carbonate and alluvial formations
- Zero to five years prior ASR operations



Results of WRF ASR Research: Non-detects and Rejects

Constituents Not Detected

- Cadmium
- Mercury
- Cyanide
- Coliphage
- Progesterone
- Diazinon
- Aldrin
- Dieldrin
- most PBDE congeners
- Bromate, Iodate

Constituents Rejected

- BHT
- DEET
- Estradiol
- NDMA
- Nonylphenol

Repeatedly
present in
lab and/or
travel
blanks



Results: Microbiota

- Each pathogen/indicator found only once:
 - Fecal Coliform
 - E. Coli
 - Enterococci
 - Giardia
 - Crypto
- No pattern with detects
- TC and HPC often detected, usually increased with time



City of Woodland CA
ASR Well 29



Results: Microcontaminants Detected but Not Trendable

Criterion: Present in recharge water $\geq 5x$ MDL

0 sites

- BDE # 28
BDE #47
- Bisphenol A
- Chlorpyrifos
- Estradiol
- Triclosan

1-2 Sites

- Acetaminophen
- Atrazine
- BHC
- Caffeine
- Diazepam
- Diclofenac
- Erythromycin
- Estriol
- Ethynylestradiol
- Fluoxetine
- Gemfibrozil
- Hydrocodone
- Naproxen
- Oxybenzone
- Perchlorate
- Sulfamethoxazole
- Testosterone
- Trimethoprim



Results: Trendable Microcontaminants

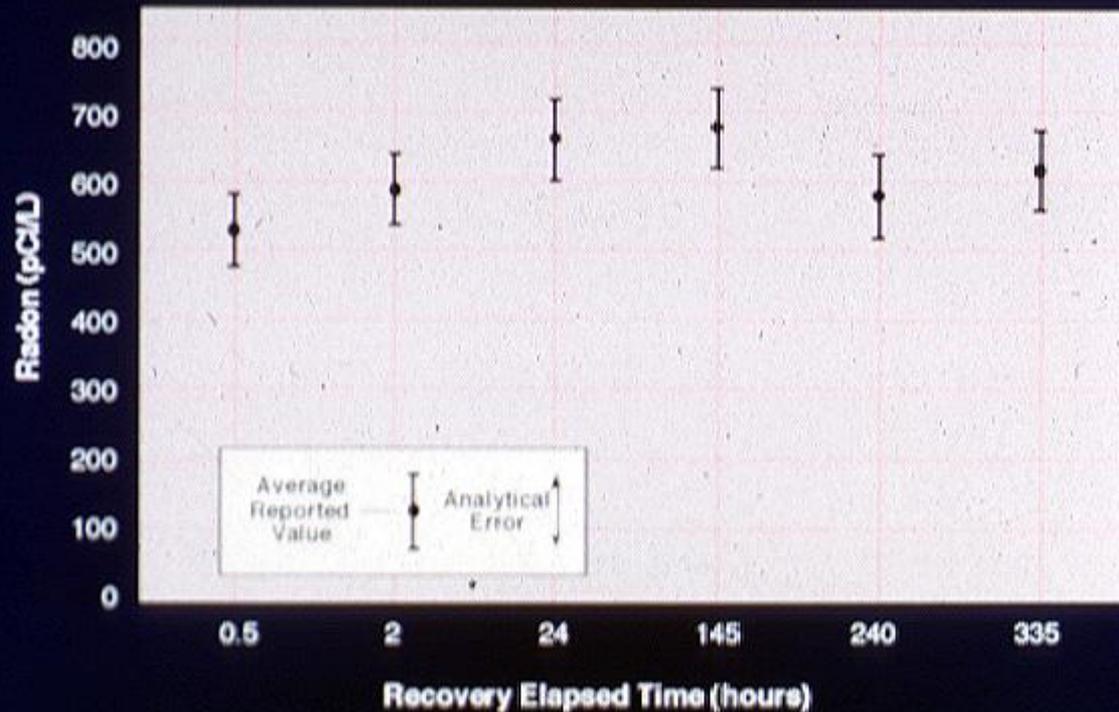
Present in Recharge Water ³ 5 x MDL at 3 or 4 Sites

	Increased	Inc./Dec. or Stable	Decreased
Carbamazepine	████████████████████	████	
Dilantin	████	████	████████████████
Ibuprofen	████████████████████	████	████
Iopromide	████████████████████	████	████
TCEP	████████████	████	████████████████
Androstenedione	████████████		
Chlorate	████████████		████████████████
Estrone	████		
Fluoranthene		████	████████████████
Meprobamate		████	████
Pentoxifylline	████████████	████████	



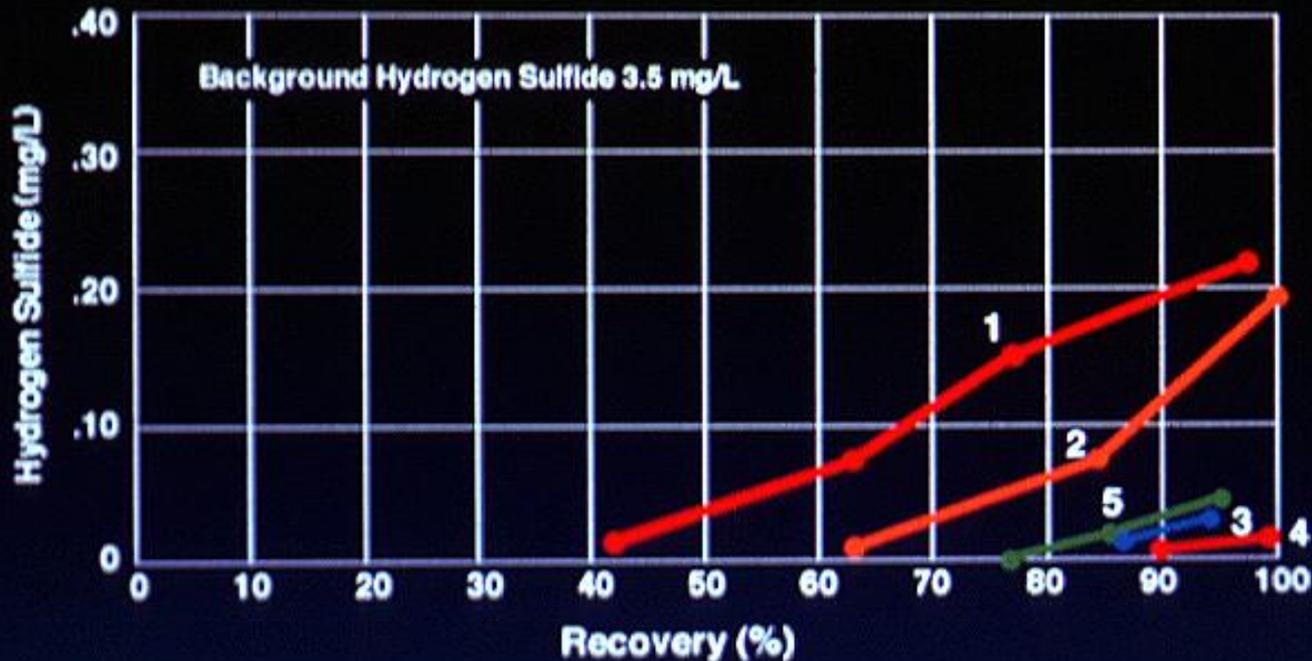
Seattle: Radon does not attenuate during ASR storage

Radon in Recovered Water vs. Pumping Time



Hydrogen sulfide typically attenuates rapidly during ASR storage

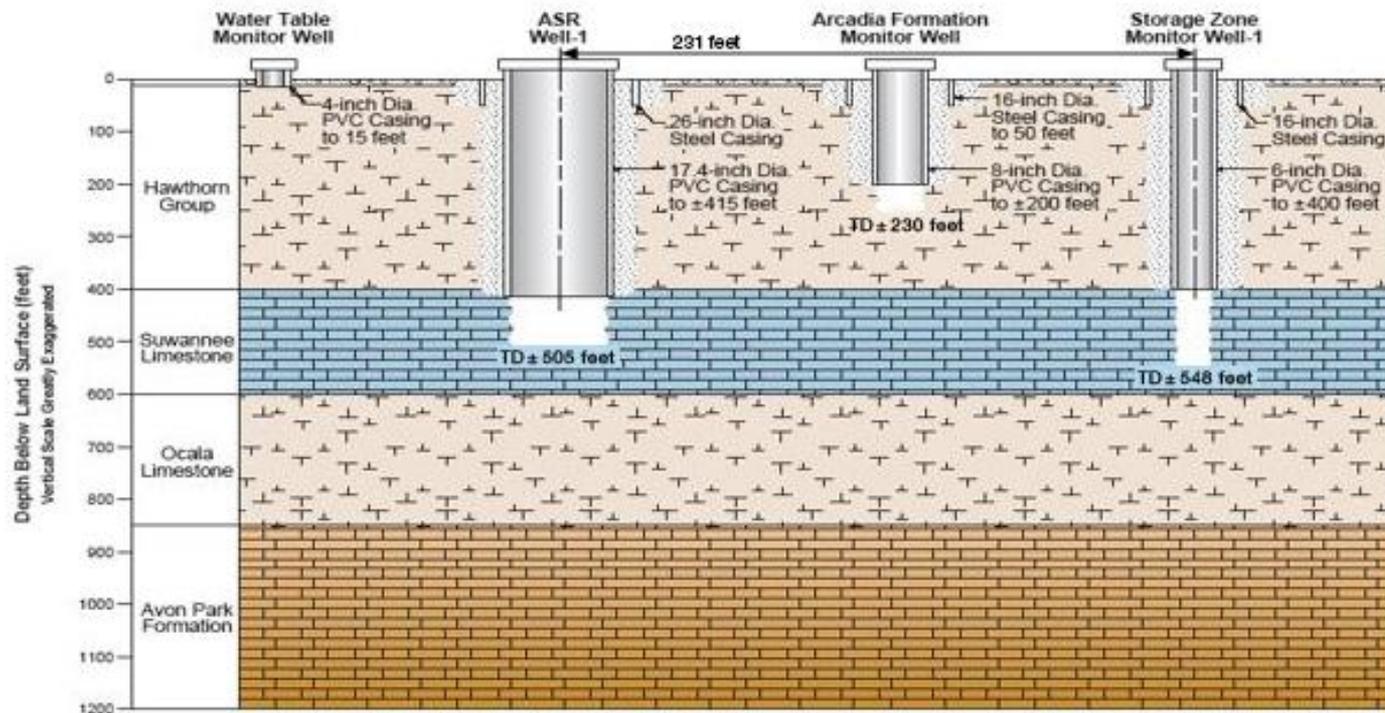
Cocoa ASR Hydrogen Sulfide Concentrations Cycles 1-5



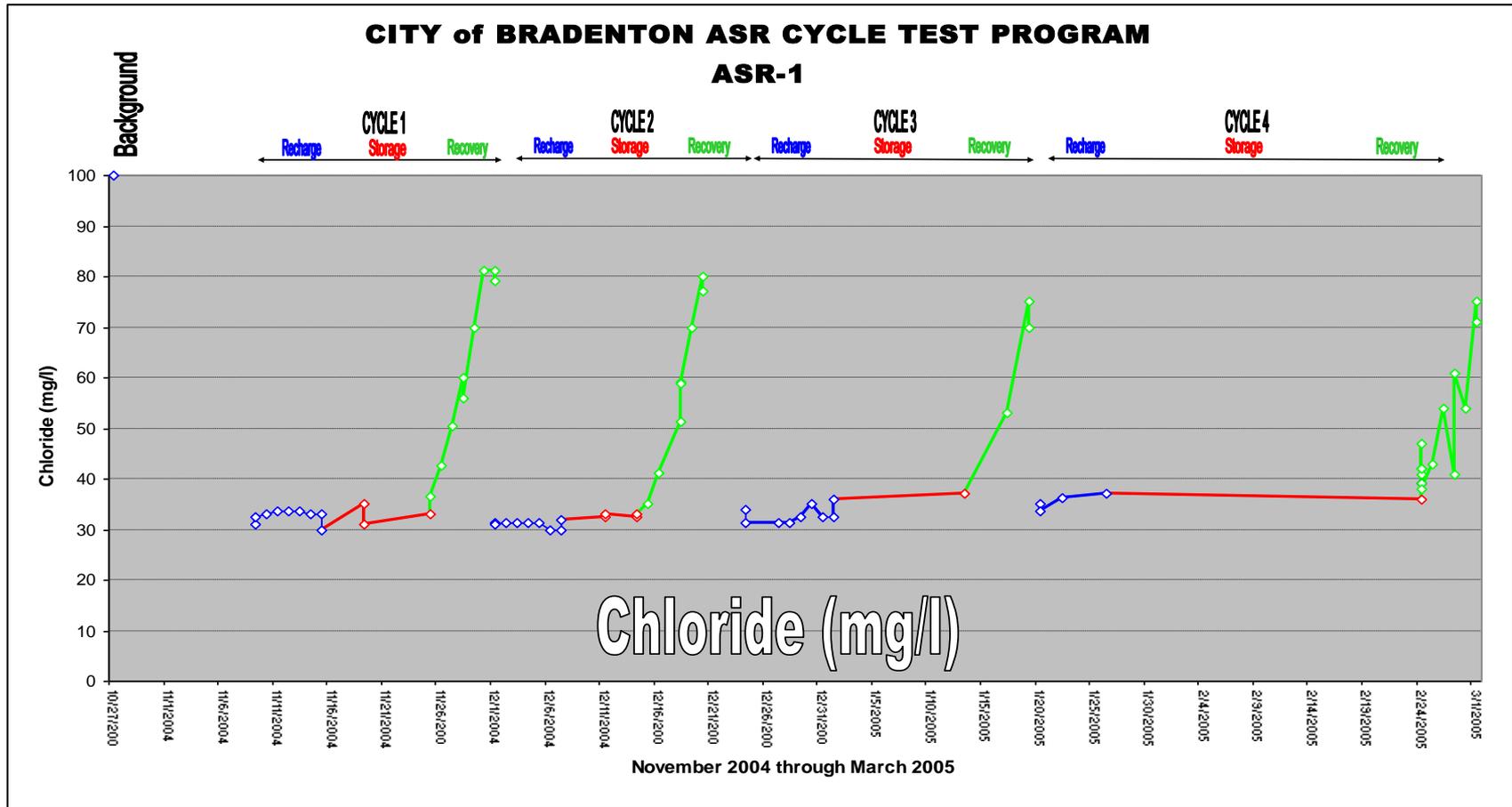
Bradenton, Florida, ASR Well Cycle Testing Data



Bradenton, Florida - ASR Well and Observation Wells



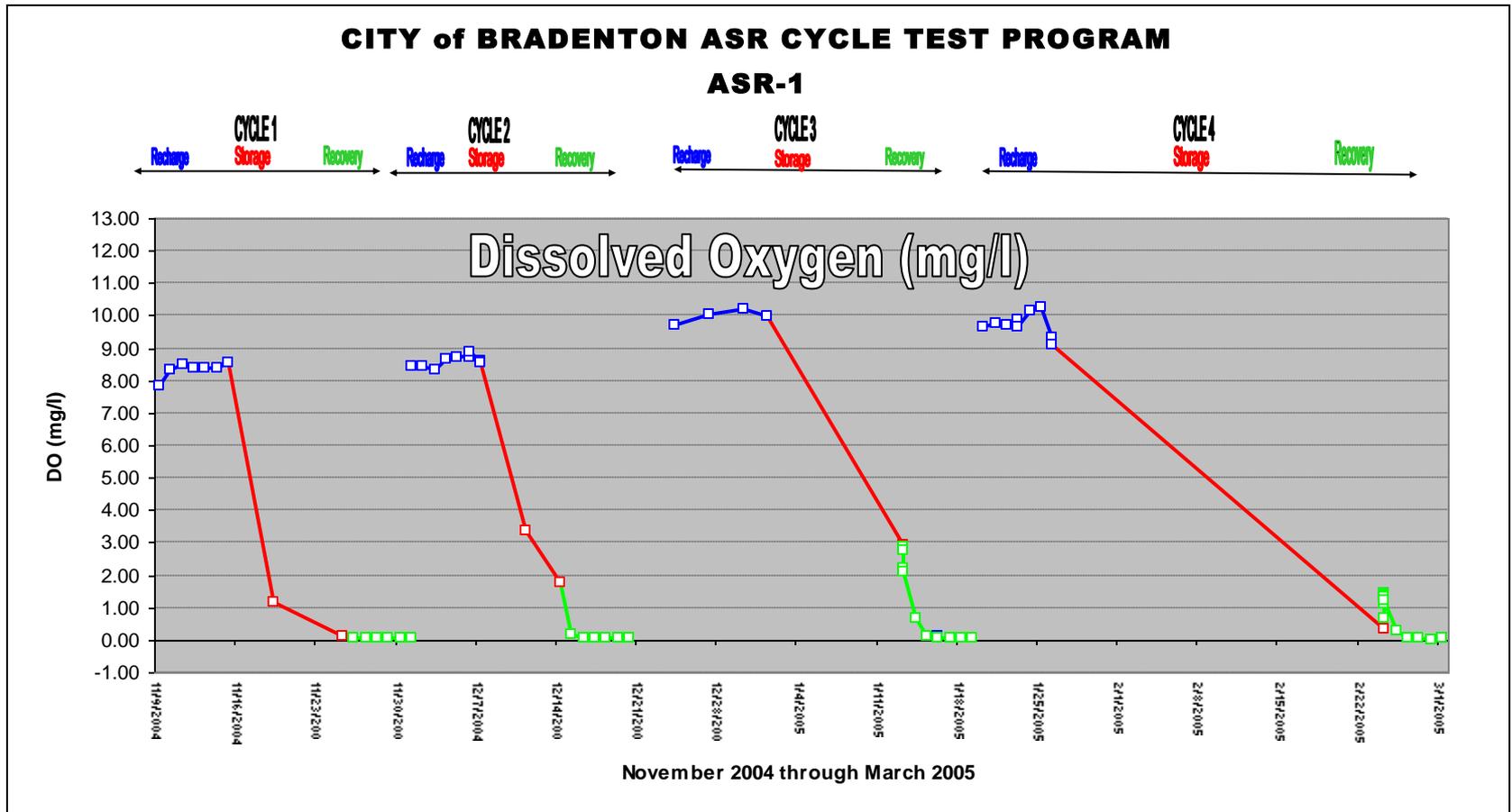
As a natural tracer, Cl⁻ may help with achieving an understanding of subsurface geochemical and microbial reactions



Cycles 1 – 4, 10 MG recharge, 10 MG recovery. Storage periods 7 days for Cycles 1-3; 28 days for Cycle 4



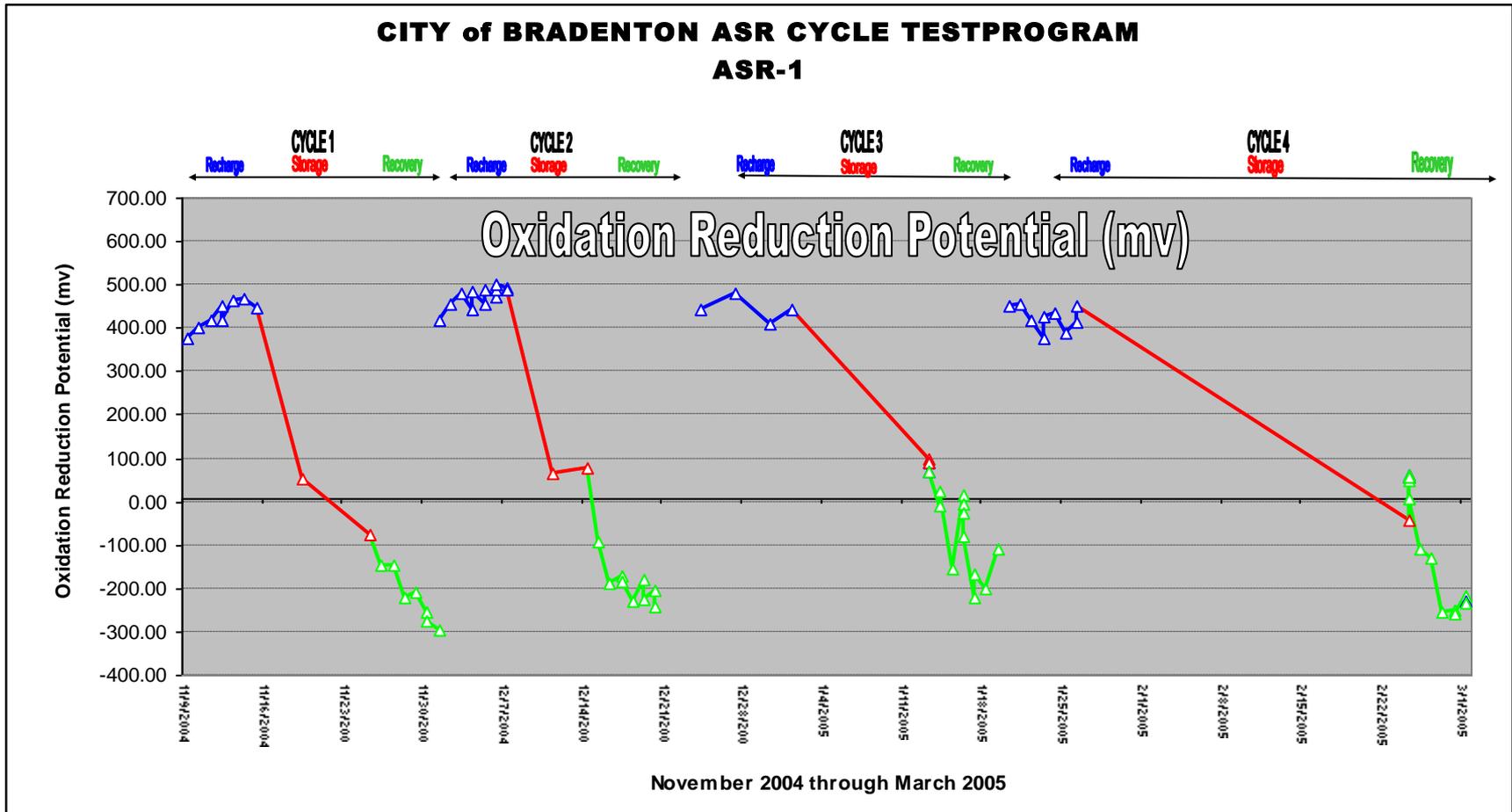
Dissolved Oxygen declined from 8 - 10 mg/l to 1 - 3 mg/l in 3 days and to 0.2 mg/l in 31 days



Cycles 1 – 4, 10 MG recharge, 10 MG recovery. Storage periods 7 days for Cycles 1-3; 28 days for Cycle 4



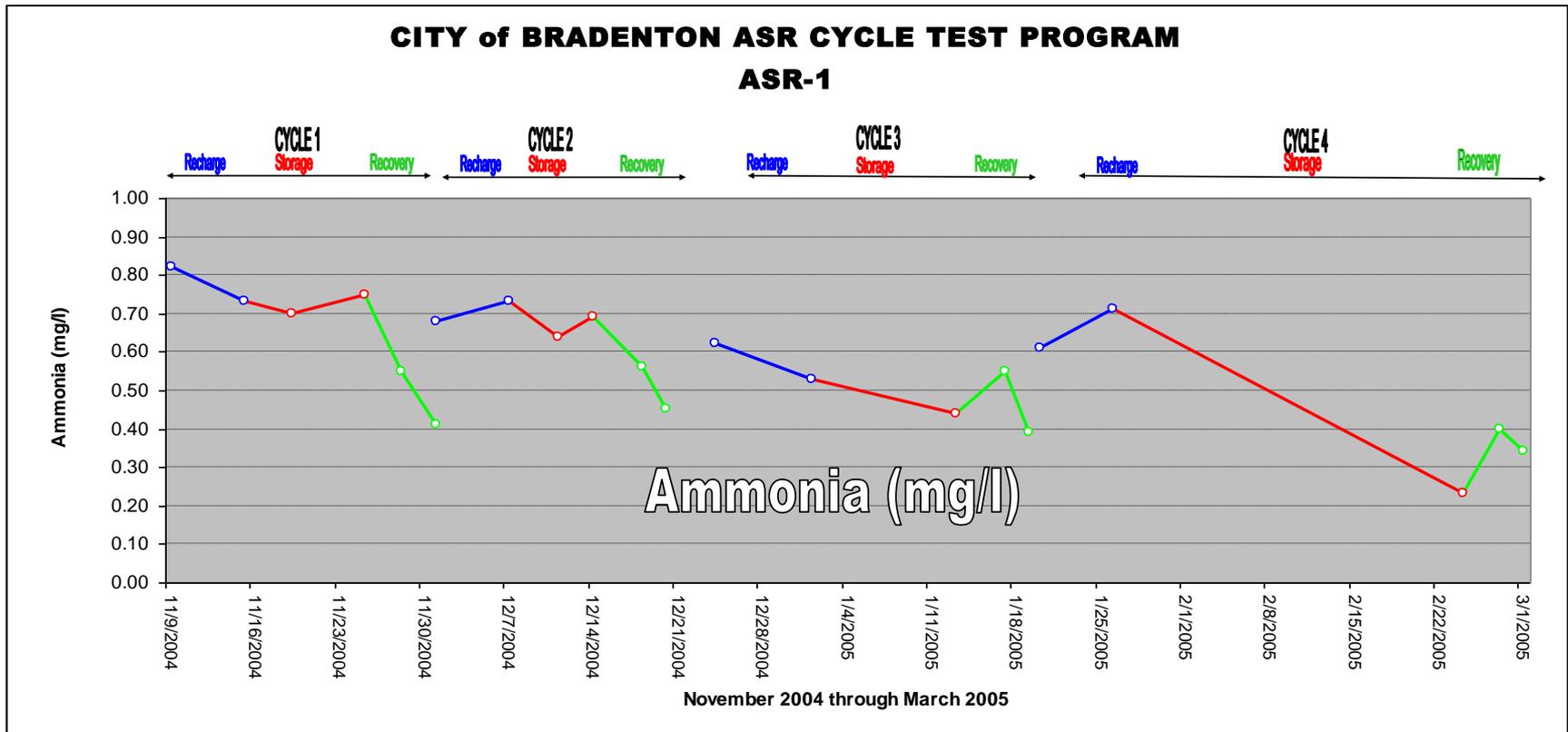
ORP declined from +450 mv to +50 mv in 3 days, and to -50mv in 28 days of storage, dropping further to -280 mv during recovery



Cycles 1 – 4, 10 MG recharge, 10 MG recovery. Storage periods 7 days for Cycles 1-3; 28 days for Cycle 4



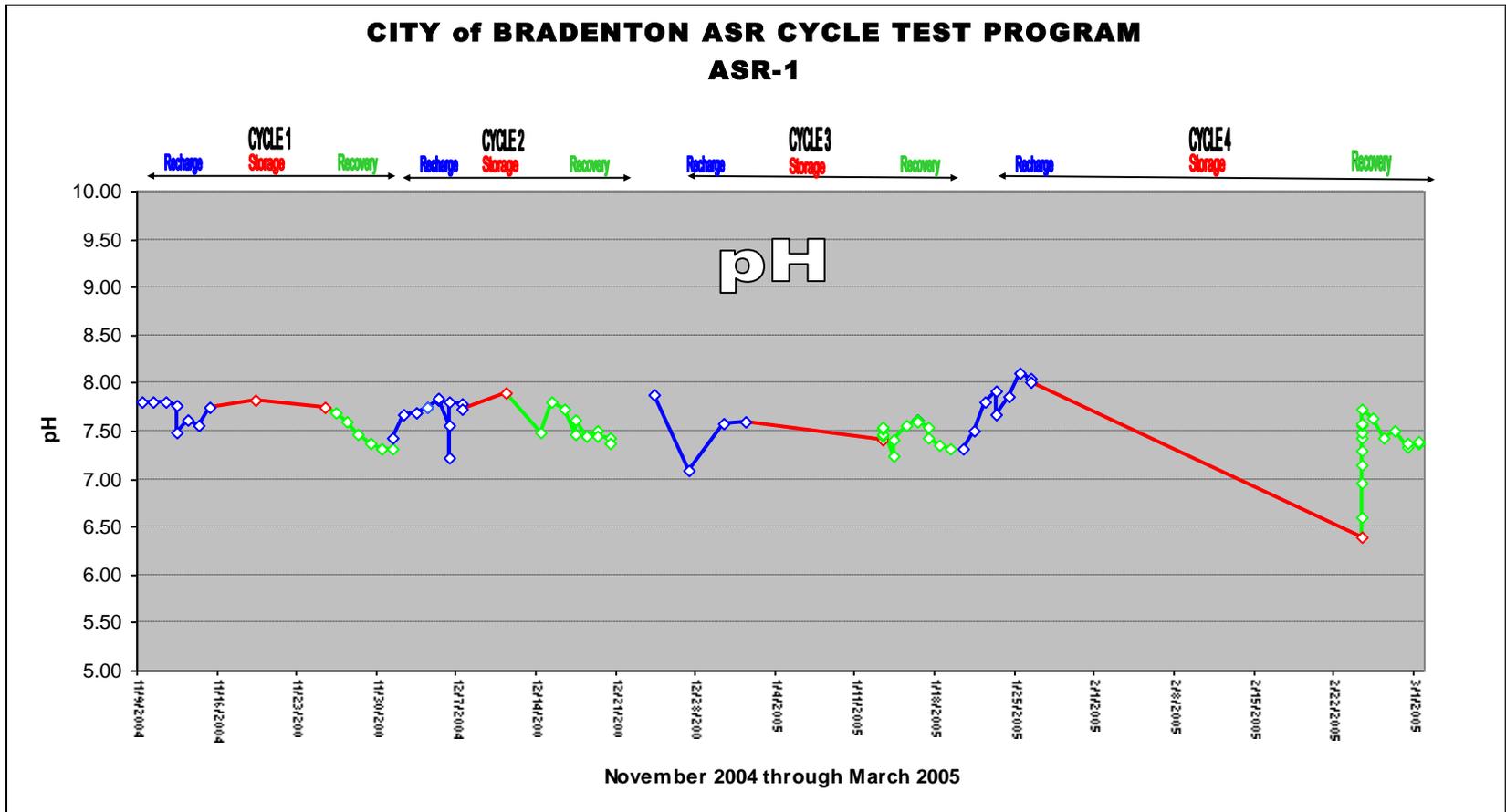
Ammonia declined about 50% during one month of ASR storage, at Bradenton and also at Palm Bay



Cycles 1 – 4, 10 MG recharge, 10 MG recovery. Storage periods 7 days for Cycles 1-3; 28 days for Cycle 4



pH during the first two hours of Cycle 4 recovery climbed from 6.4 to 7.7, and then stabilized at 7.3



Cycles 1 – 4, 10 MG recharge, 10 MG recovery. Storage periods 7 days for Cycles 1-3; 28 days for Cycle 4



Design Considerations for ASR Well Facilities

- Unique design features for
 - ASR Wells
 - ASR Wellheads
 - ASR Wellfields
- Understanding these unique features can help to ensure a successful well recharge program.
- Design and testing scale
 - Think small, get small results
 - Think big, get big results



Need effective integration of hydrogeologic and engineering tasks

- Casing diameter sufficient to accommodate well equipping requirements
- Provision for annulus recharge at wellhead
- Drawdown measurement tube set deep enough
- Drawdown and other tubes oriented correctly at wellhead flange relative to subsequent piping, and far enough laterally from pump column
- Monitor well diameters
- Materials of construction
- Screen collapse strength
- Well grouting
- Treatment process design integration with well design



Selected Wellhead Design Features

- Redundant water level/pressure measurement capability (transducer, electric tape, bubbler gage)
- Redundant flow measurement capability (option)
- Motorized valves linked to SCADA
- Water lubricated pump
- Trickle flow bypass piping to control downhole microbiological activity and provide pre-lube
- Wellhead designed to hold pressure
- Recharge down pump column, casing annulus or both
- Flow meter submerged in low section of pipe
- Variable frequency drive for pump
- Air/ vacuum relief valves
- Downhole flow control valve (above or below pump)



Pump Selection

Submersible

- Noise unlikely to be a problem
- Lower cost than vertical turbine
- Power consumption higher than turbine
- Requires more maintenance as motor fully submerged
- Greater space required within the intake chamber
- Access for maintenance is difficult
- Cannot recharge through pump column without damaging bearings

Vertical Turbine

- More efficient than submersible
- Maintenance on pump head easier due to dry access
- Requires long vertical shaft (time to install & remove)
- Intake chamber size is reduced compared to submersibles
- Capable of operating at great depths
- More tolerant of sand production
- Higher cost than submersible pumps
- More time consuming to retrieve intake and replace impellers



Recharge Pressures and Fracking Concerns

- Typical pressure in casing annulus at wellhead flange less than 30 psi
- Formation pressure will depend on depth to static water level and friction loss in subsurface piping
- Depth to static water level may depend on variable water column density
- Fracking is frequently a source of public concern but has not been a significant issue for ASR



Casing design considerations

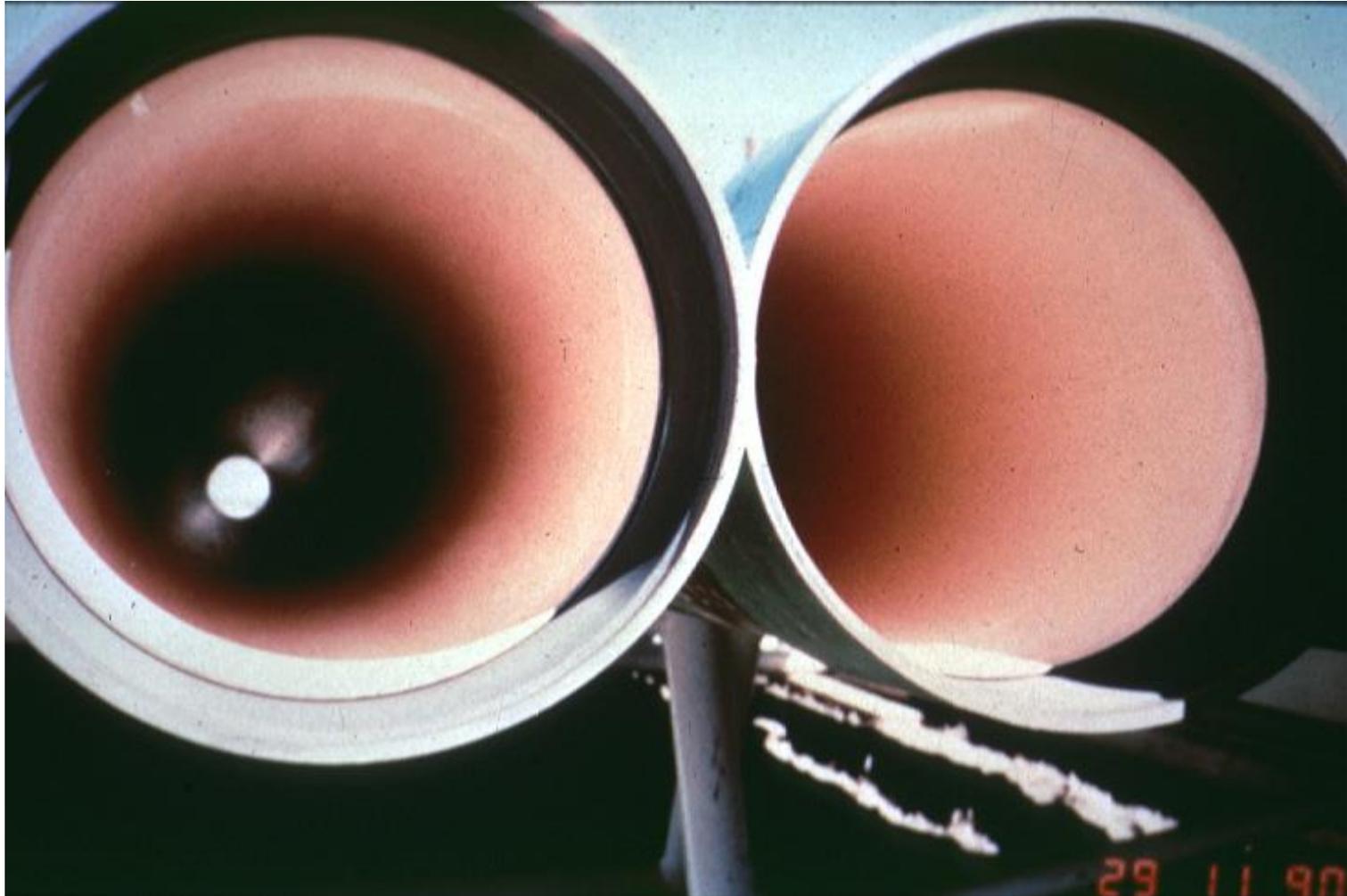
- Materials of construction to address internal and external corrosion
- Diameter to provide for pump, column, flanges, tubing, etc.
- Collapse strength and tensile strength during installation
- Abrasion resistance
- Borehole diameter



Murray Avenue ASR
Well, Cherry Hill, NJ



Kerrville, Texas, ASR Well – Internal Epoxy-Coated Steel Casing



Rubber Bumpers on Drill Pipe to Protect Epoxy-Coated Casing



PVC Casing

- Certa-Lok 17.4" OD (15.3" ID) SDR-17 casing has been the largest diameter commonly available, until recently
- 24" OD, SDR-17 is now available
- Depths to over 1,000 ft.
- Heat of hydration requires careful installation and cementing procedures, therefore greater construction risk.
- Appropriate for ASR wells since non-ferrous, therefore no corrosion products.



Stainless Steel (SS304L, SS316) and HSLA

- Las Vegas Valley Water District, Nevada
 - Delray Beach, Florida
 - City of the Colony, Texas (designed but not constructed)
 - Orangeburg, South Carolina
 - Wilmington, North Carolina
 - Oxnard, California
 - Stainless steel spline connections for column piping address galling concerns
- Expensive, but...
strong,
and essentially no
corrosion
products.**



Fiberglass Casing

- Large diameter applications are fairly new
- Double O-ring connections designed to achieve mechanical integrity of well casing under pressure
- At least three manufacturers to date making large diameter FRP casing for wells
- Several 24” FRP-cased wells completed to date
- Issues with strength, joint connections, cementing requirements in large diameter holes



Screen Design

- Not much different design approach than for conventional water supply wells
- Generally use rod-based, wire-wrapped stainless steel screens for maximum efficiency
- Extra-strength rods/wires, or pipe-based for even more strength
- Louvered screens provide additional strength but with reduced efficiency
- PVC screens are often used in Europe
- Other options: slotted, torch-cut screens and gravel packs; underream, “Muni-Pak.”



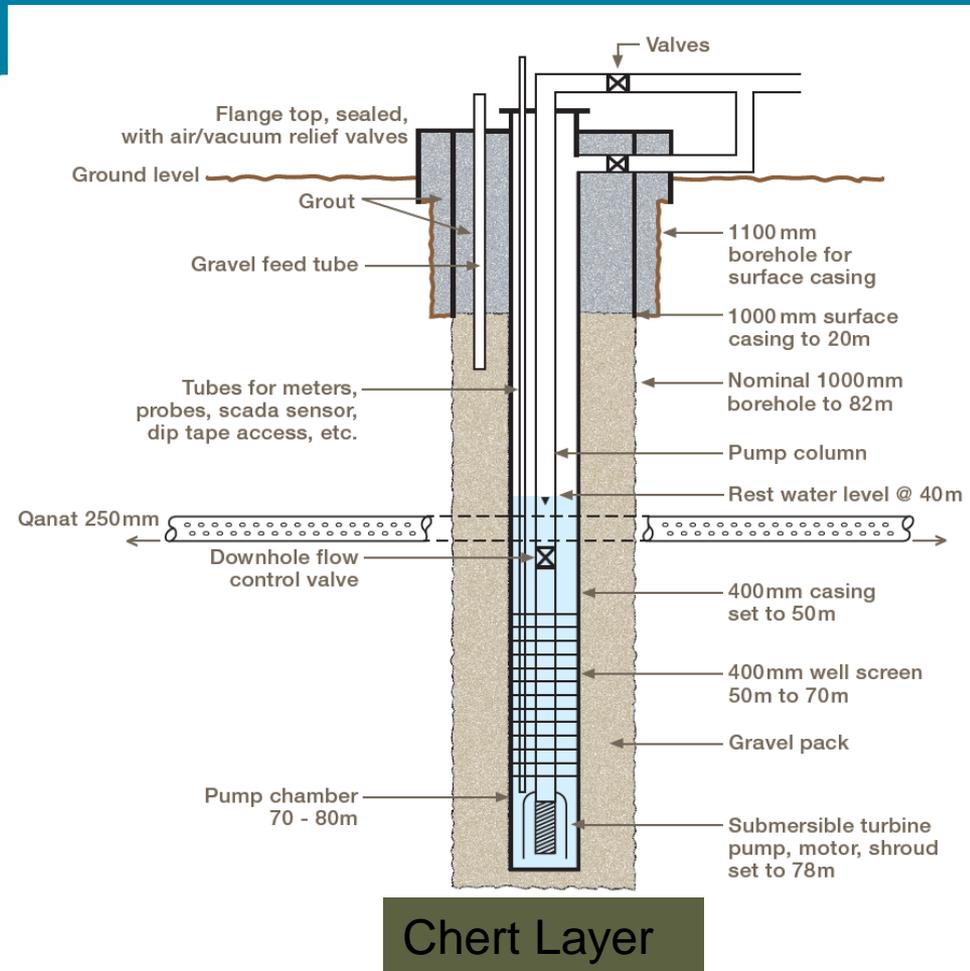
Filter Pack Selection

- Avoid angular, non-silica gravel pack
- Select high quality silica gravel graded to match screen slot size and formation gradation
- Consider use of glass beads (SiLibeads) to enhance well efficiency and yield while reducing well development time
 - more expensive
 - better well performance
 - well construction is usually relatively inexpensive; equipping and operating wells is usually far more expensive



ASR Well Conceptual Design:

- Unusual application
- Interconnect Rus and upper UER aquifers with a single ASR well, above a chert layer
- Large diameter casing to deal with potential air entrainment
- Large borehole diameter to facilitate storage and recovery within the unsaturated Rus
- **SiLibead filter pack to improve well yield and efficiency by moving water vertically through the filter pack during recharge and recovery**
- Pump seasonally at below design rate, using VFDs

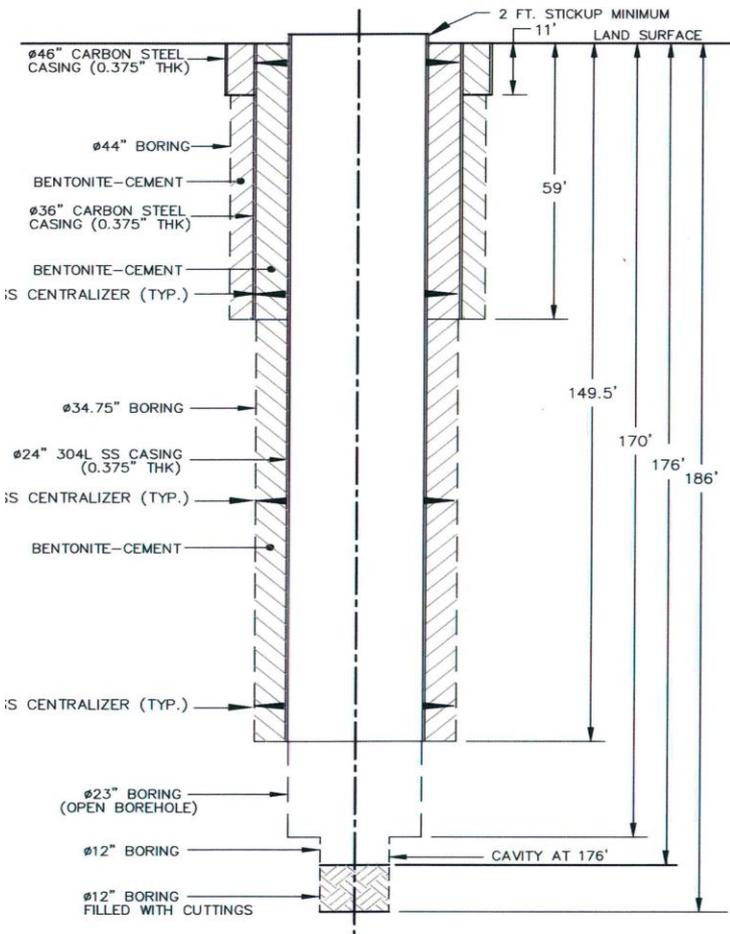


ASR WELL CONCEPTUAL DESIGN

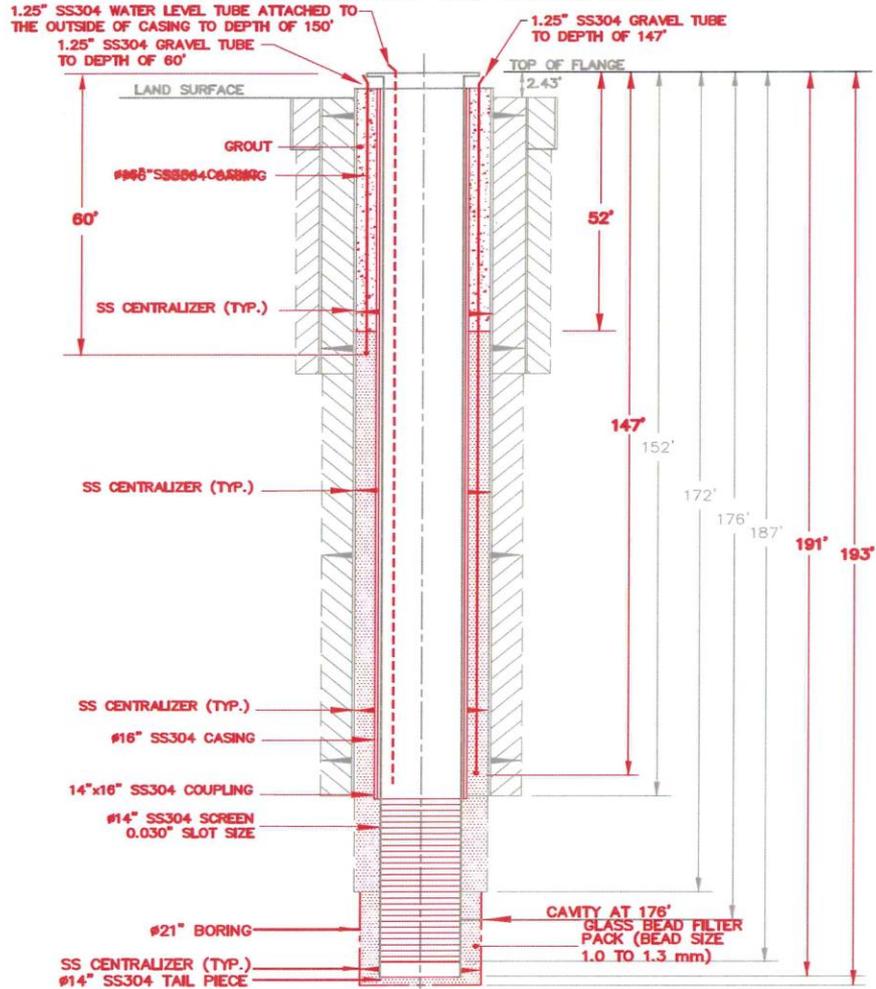


Wilmington NC _ SiLibeads Application

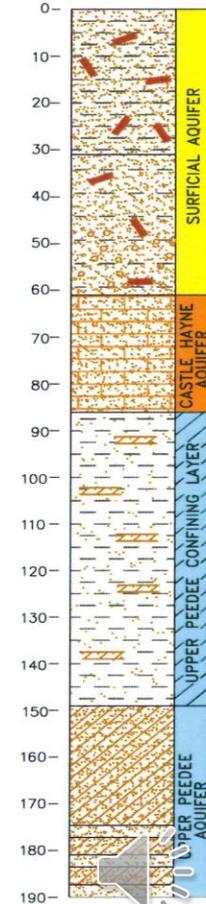
ASR-1
EXISTING BOREHOLE CONSTRUCTION



ASR-1
PROPOSED SCREEN AND GRAVEL PACK



FT. BLS LITHOLOGY



Wilmington NC Westbrook ASR Well

CAPE FEAR PUBLIC UTILITY AUTHORITY



Screen Development

- Different for injection/ASR wells than for water supply wells
- Do conventional well development first, then conduct a series of injection slugs followed by pumping, to further develop the gravel pack and remove fine materials for bi-directional flow. As turbidity improves, step up the injection flow rate and volume, and repeat.
- Increases well yield and efficiency substantially
- Tom Morris/West Yost - Radial Injection Surge Development (RISD) method, developed at Las Vegas and successfully applied for NASA at White Sands Test Facility, New Mexico, and many other sites.



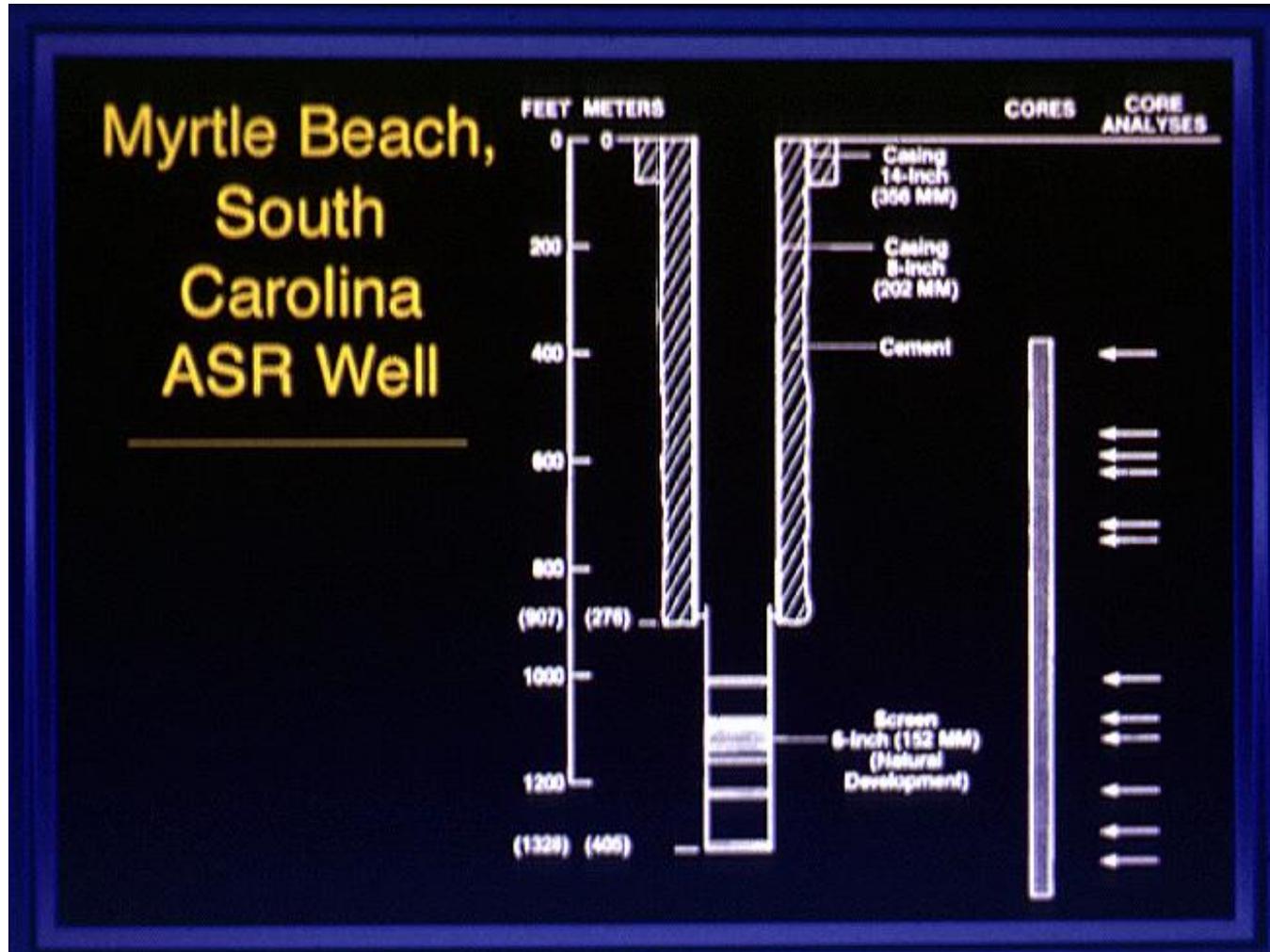
Storage Zone Selection

- Different than for production or injection wells
- Tend to prefer single zones with adequate confinement over multiple zones with higher total yield
- Tend to case out zones with geochemical problem constituents
- Consider potential for density stratification and for regional lateral groundwater movement
- Greater reliance upon acidization, greater drawdowns, and possibly other measures such as horizontal directional drilling (HDD), to achieve high recovery rates
- With 2 or more storage intervals, rely upon a larger buffer zone volume in aquifers with poor ambient water quality
- “Stacking” storage intervals



Coring and Core Analysis

Myrtle Beach, SC



Myrtle Beach, South Carolina



Myrtle Beach, SC



Myrtle Beach ASR Core Analysis Results

X-Ray Diffraction	Middendorf	Black Creek
Quartz	76 – 85%	77 – 95%
Calcite	0 – Trace	Trace – 1
Dolomite	0 – 1	0 – Trace
Pyrite	0	0 – 2
Kaolinite	2 – 4	0
Chlorite	0	0 – Trace
Illite/Mica	1 – 2	Trace – 11
Smectite	2 – 4	Trace – 8
Plagioclase Feldspar	1 – 7	0 – 3
K-Feldspar	7 - 11	2- 4



Myrtle Beach, SC - SEM Analysis



Wellhead downhole flow control is vital for ASR wells.

Non-Adjustable Downhole Flow Control

- Injection tubes
 - Single
 - Multiple
- Annulus flow
- Pump column flow
- Vacuum recharge (Chesapeake, Calleguas MWD) – “reverse siphon”

Adjustable Downhole Flow Control Valve

Need to handle air volume in pump column, where static water level is deep and formation could air-bind.



Adjustable Downhole Flow Control Valve Options

- Baski Downhole Flow Control Valve
- V-SMART Valve
- 3R Valve
- Grundfos Valve

Development of selection criteria and associated weighting factors helps to identify a downhole control valve that is best-suited for each ASR well requiring such a valve in order to control cascading and air binding.

Other options include a reverse siphon recharge startup approach, requiring full automation, I&C, SCADA and careful programming to deal with a potentially broad range of variability in static water levels, flow rates, recharge pressures, well hydraulics and aquifer hydraulics.



Baski Downhole Control Valve



Figure 3.12 Baski Downhole Flow Control Valve.
Source: Baski, Inc.

- In operation for over 30 years
- Hundreds of valves in service



V-Smart Valve



- In operation for over 20 years

Six-inch V-Smart Valve



3R Downhole Control Valve

Oregon, Florida, California



DHCV Control
Panel



DHCV Cutaway



Disinfection Equipment



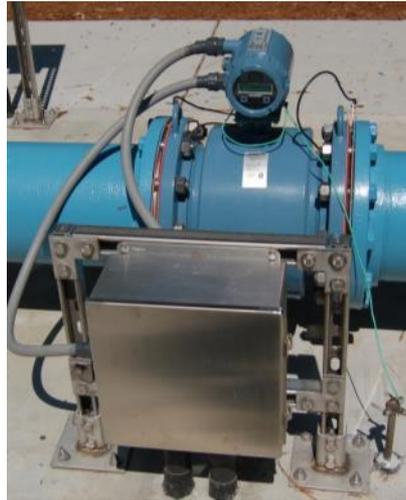
NaOCl Storage Tank
and Tank-Mounted
Feed Pump



Chlorine Residual Analyzer



Field Instruments: Pressure, Flowrate, Level, Valve Position, Conductivity, etc..



I&C/SCADA System Panel



Control Panel



Operator Interface Screen



Electrical System Panels



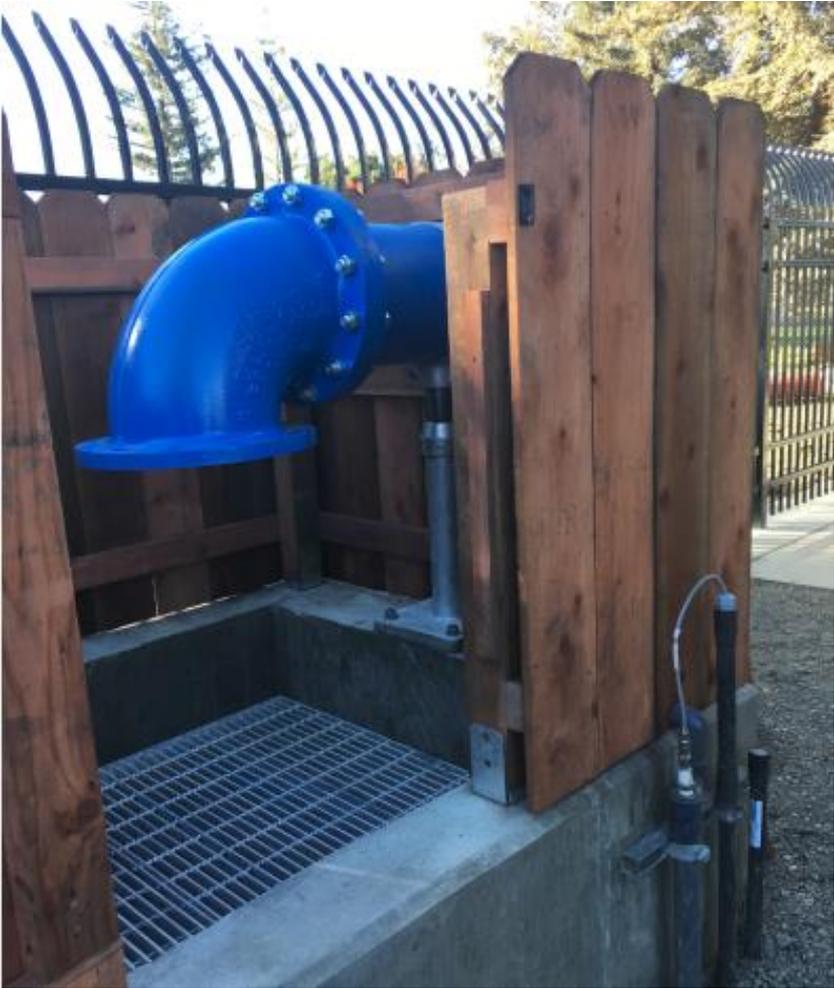
Recovery Pump Variable Frequency Drive



Motor Control Center

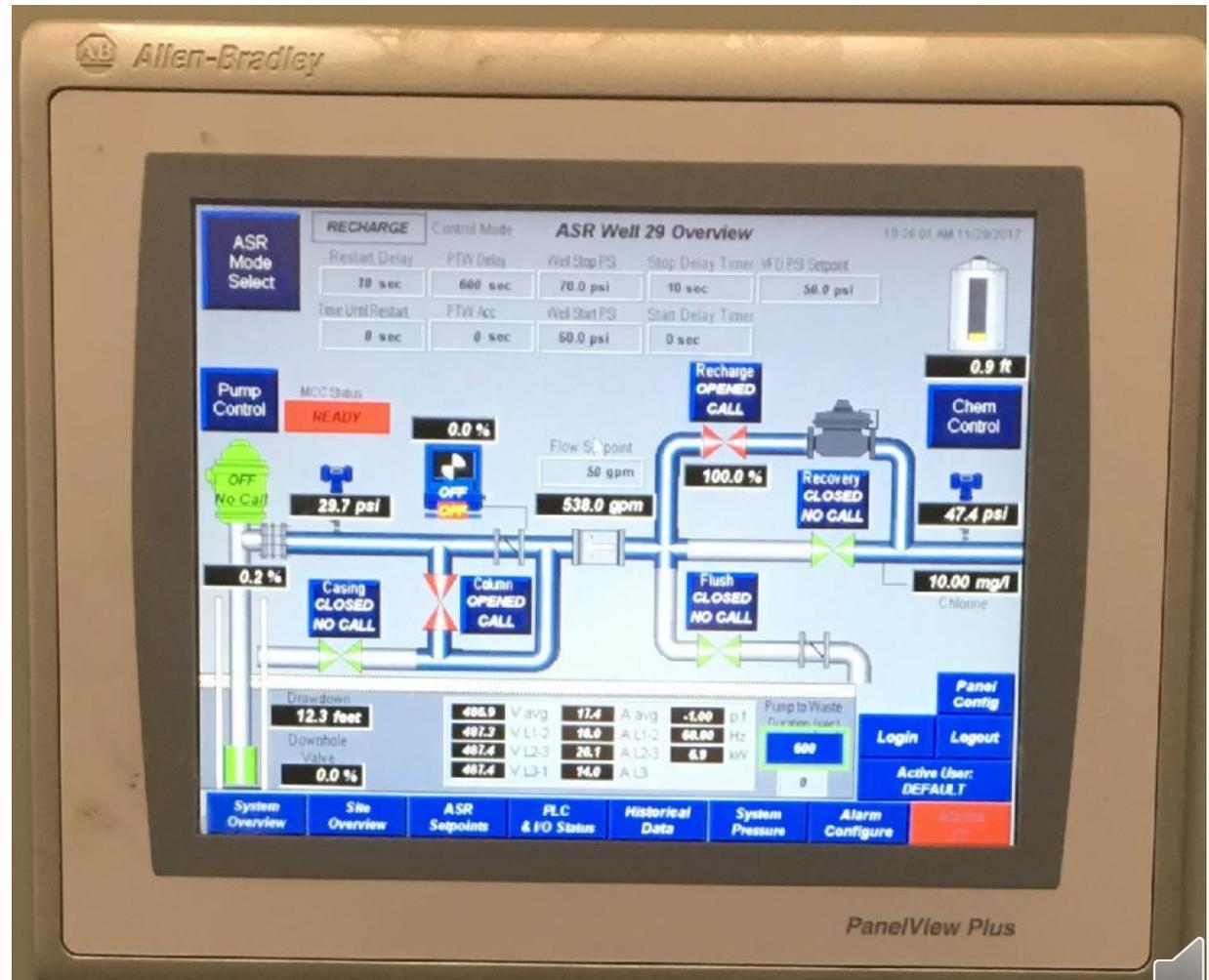


Flushing System Air-Gap Discharge



Automatic Modes of Operation & Operator Interface Screen

- Recharge
- Trickle Flow/ Storage
- Maintenance/ Off
- Flush/ Backflush
- Recovery



Pump & Valve Status for Various Modes of Operation

EXHIBIT 3-16: Pump and Valve Status for the Various Modes of Operation

Tag	Pump or Valve	Recharge	TF/Storage	Maintenance	Well Flush	Recovery
PMP3001	ASR Well Pump	Off	Off	Off	VFD On	VFD On
MOV3011	Recharge Control Valve	Modulating	Closed	Closed	Closed	Closed
MOV3012	Pump Column Recharge	Open	Closed	Closed	Closed	Closed
Check Valve	Column Recharge	Open	Closed	Closed	Closed	Closed
MOV3014*	Well Annulus Recharge	Open*	Closed	Closed	Closed	Closed
MOV3015	Recovery	Closed	Closed	Closed	Closed	Open
MOV3016	Aquifer Flush	Closed	Closed	Closed	Open	Closed
POV3013	DHCV	Open	Closed	Closed	Passive	Passive
PMP3021/22	NaOCl Metering Pump	Off	Off	Off	Off	On
Check Valve**	Suction Check	Closed	Closed	Closed	Open	Open

Notes:

* The annulus recharge valve shall only open if needed to meet recharge set point, and with >2 psi pressure in annulus.

** The suction inlet check valve closes automatically during Recharge and opens automatically for Flushing or Recovery.



Operating Mode: Backflush to Waste

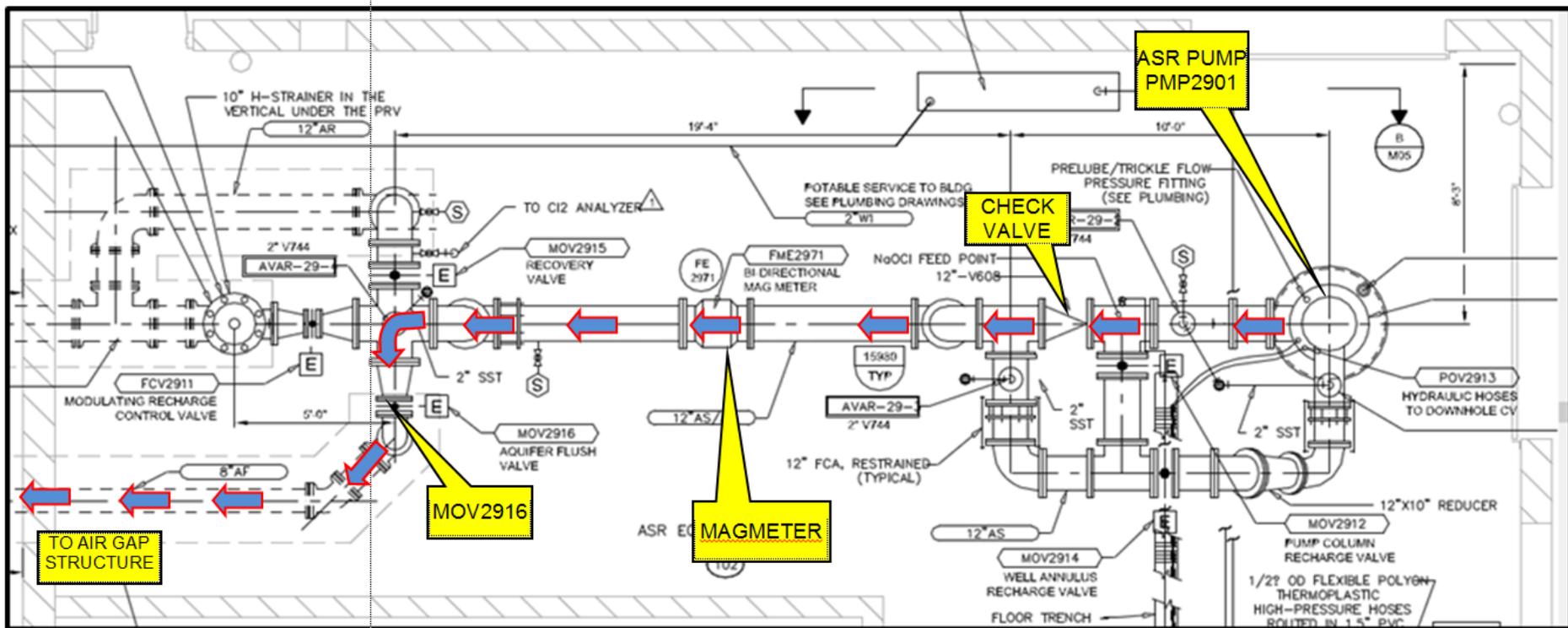


EXHIBIT 3-14: Back-flush Mode Flow Path



Operating Mode: Recovery to Distribution System

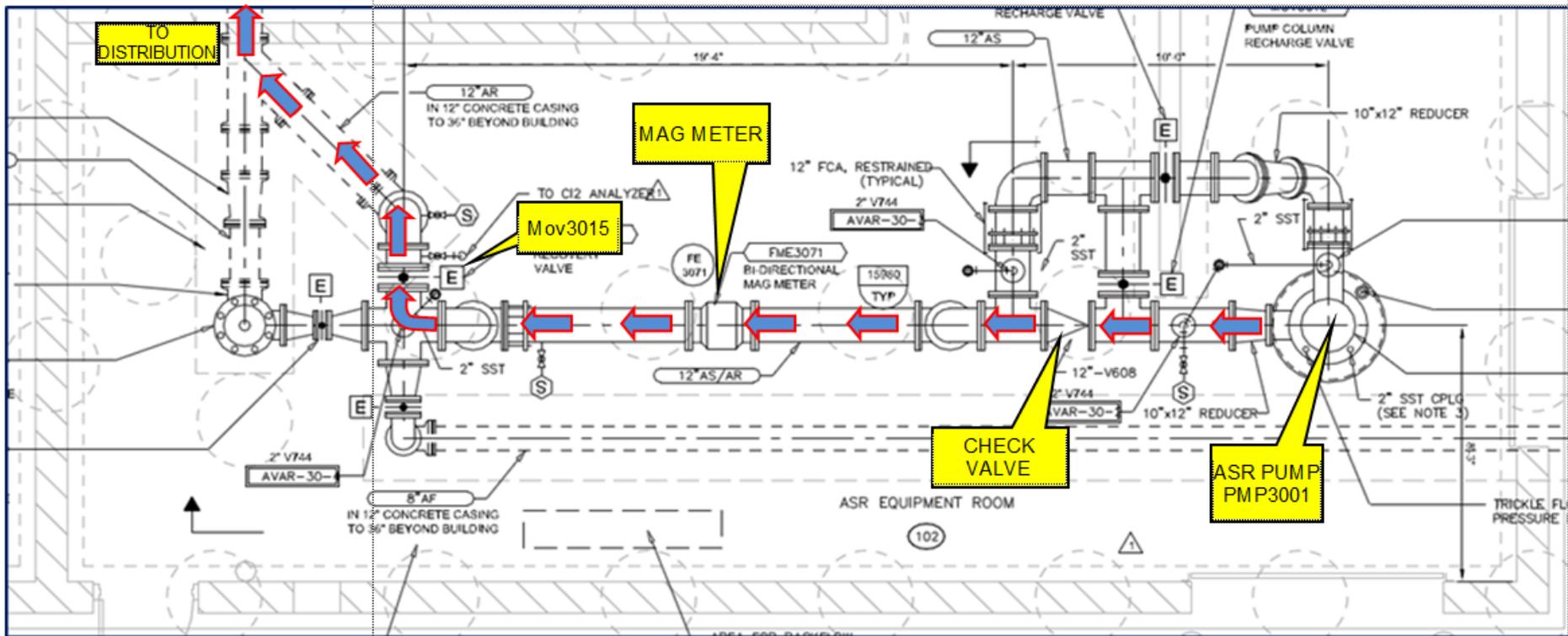


EXHIBIT 4-14: Recovery Mode Flow Path



Cycle Testing Program

ASR Cycle Testing Plan								
City of Woodland Well ASR-29								
November 2017 to September 2019								
Activity	Approximate Duration (days)				Estimated Volume (MG)			Comments
	Recharge	Storage	Recovery	Cumulative	Recharge	Recovery	Cumulative	
Cycle Test One	60	2	5	67	120	15	105	November 2017 to February 2018
Cycle Test Two	70	60	35	165	140	105	140	March 2018 to September 2018
Cycle Three	180	60	100		360	300	200	October 2018 to September 2019
Notes:								
1. Assumes average recharge flow rate of 2.0 MGD, varying between 1.5 and 2.5 MGD								
2. Assumes recovery flow rate averaging 3.0 MGD, varying between 2.5 and 3.5 MGD								
3. Assumes Cycle One occurs during November 2017 to February 2018 with recovery to waste								
4. Assumes Cycles 2 and 3 recover water to the distribution system								
5. Flow rates, durations and volumes will vary to match operational needs, constraints and opportunities								
6. Assumed Target Storage Volume is 500 MG, of which 324 MG is available for recovery and 176 MG is buffer zone								



Cycle Testing Program Assumptions and Uncertainties

- ASR feasibility study estimates of flows, levels, water demands, water quality, regulatory criteria, ASR objectives, etc
- Well hydraulic response to recharge. Ratio of specific capacity during injection (SC_i) to specific capacity during pumping (SC_p) is typically estimated then confirmed.
- Recharge water quality; seasonal water supply and demand constraints
- Water rights constraints
- Variable static water levels; density differences
- Interim recharge, or not?
- Uncertain geochemistry; backflush frequency/ procedure



ASR Recharge Startup

- Punch List for Construction of Wellhead/Downhole Facilities
- Baseline sampling, static water levels (ASR and monitor wells)
- Equipment performance testing
- O&M Manual (draft and final)
- Training program
- System Performance Testing
- I&C/ SCADA system adjustments to control logic (time delays, dead bands, set points, pressures, flows, water levels, etc)
- Onsite coordination needed between design engineer, I&C programmer, and water utility operations staff
- Weekly/ monthly monitoring of historian data, and operational adjustments, as appropriate

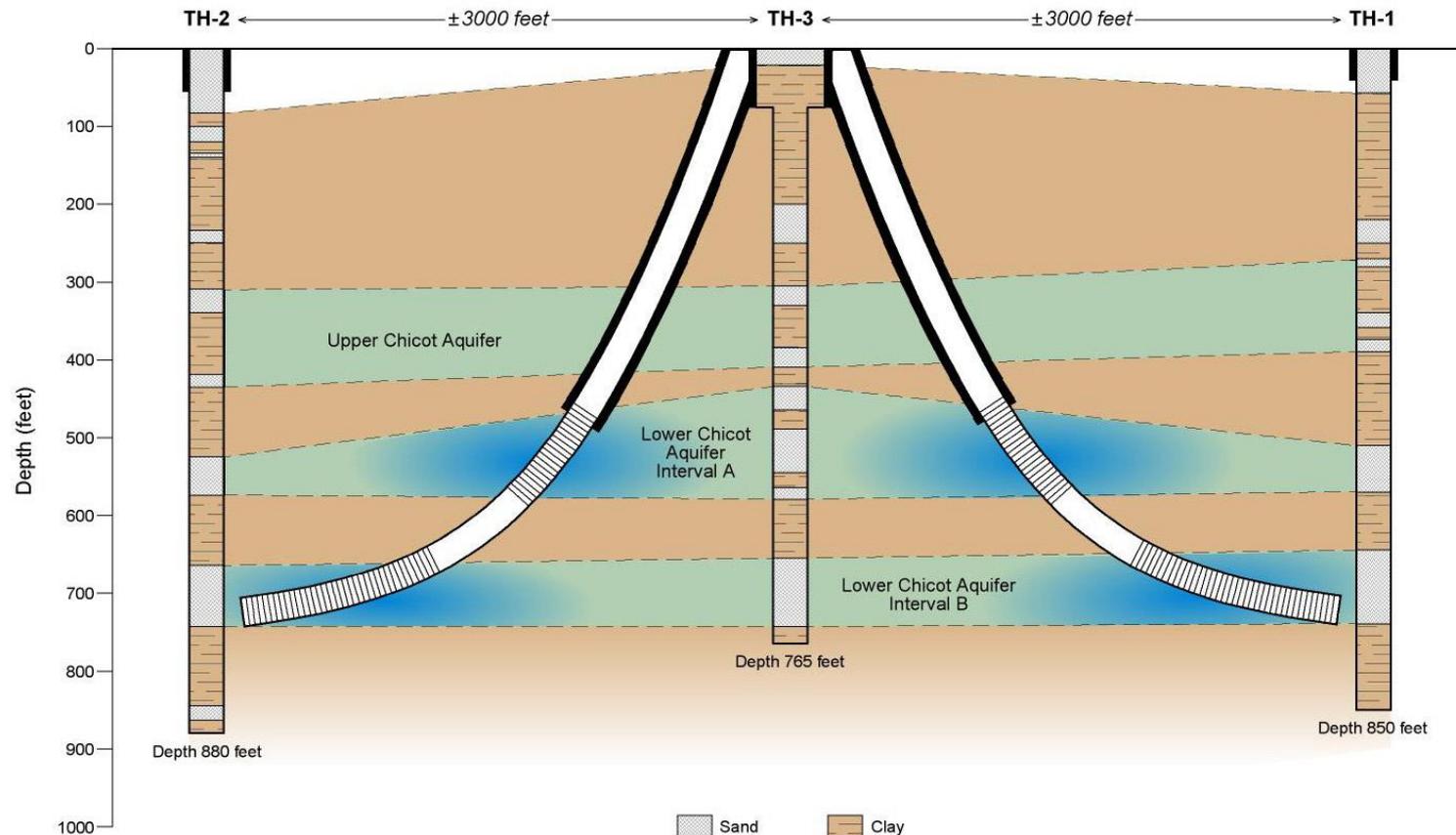


Horizontal Collector Wells

- Provide water supply and bank filtration
- Ranney® Wells
 - Vertical caisson with radial bored collectors, up to around 30 m deep
 - Decades of U.S. and Europe experience
 - Sonoma County Water Agency, California, and many other sites
 - Three sites use these in reverse for aquifer recharge
- Deep trenches with horizontal collectors, up to about 8 m deep
- Horizontal Directionally Drilled (HDD) wells
 - Technology frontier for water well industry
 - Screen lengths and depths up to about 300 m (1,000 ft)
 - Diameters up to about 400 mm (16 in)
- Combination of HDD and vertical wells can enhance yield and reduce overall costs in many ASR and normal wellfield situations
- Patented technologies



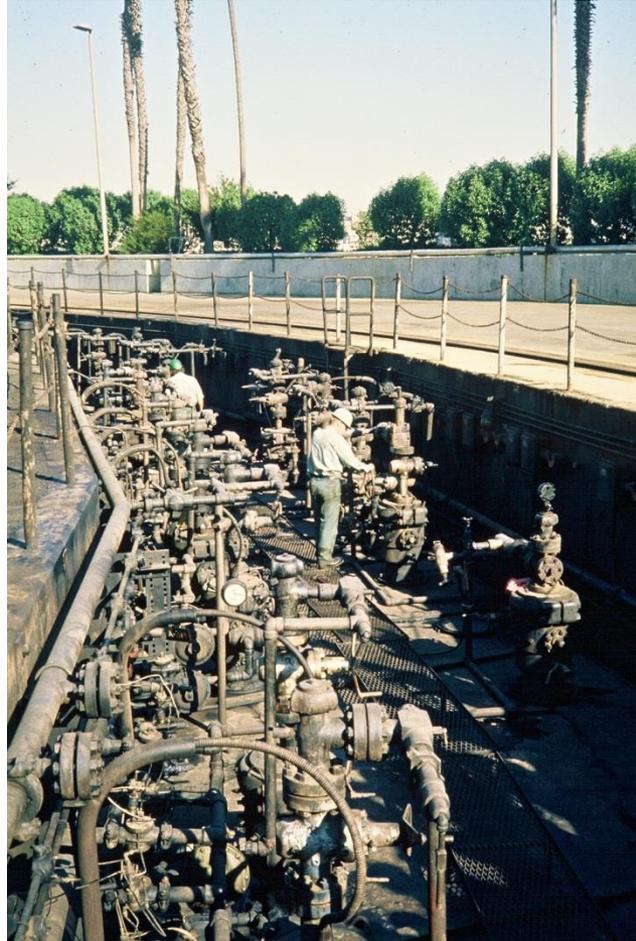
Horizontal Directionally-Drilled (HDD) ASR Wells can meet water storage needs in shallow aquifers



Long Beach Well Island

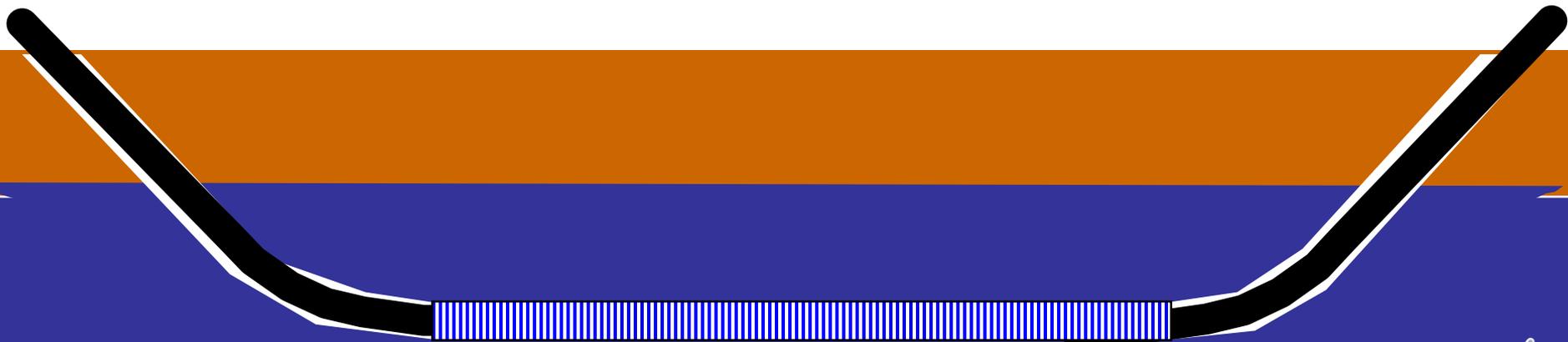


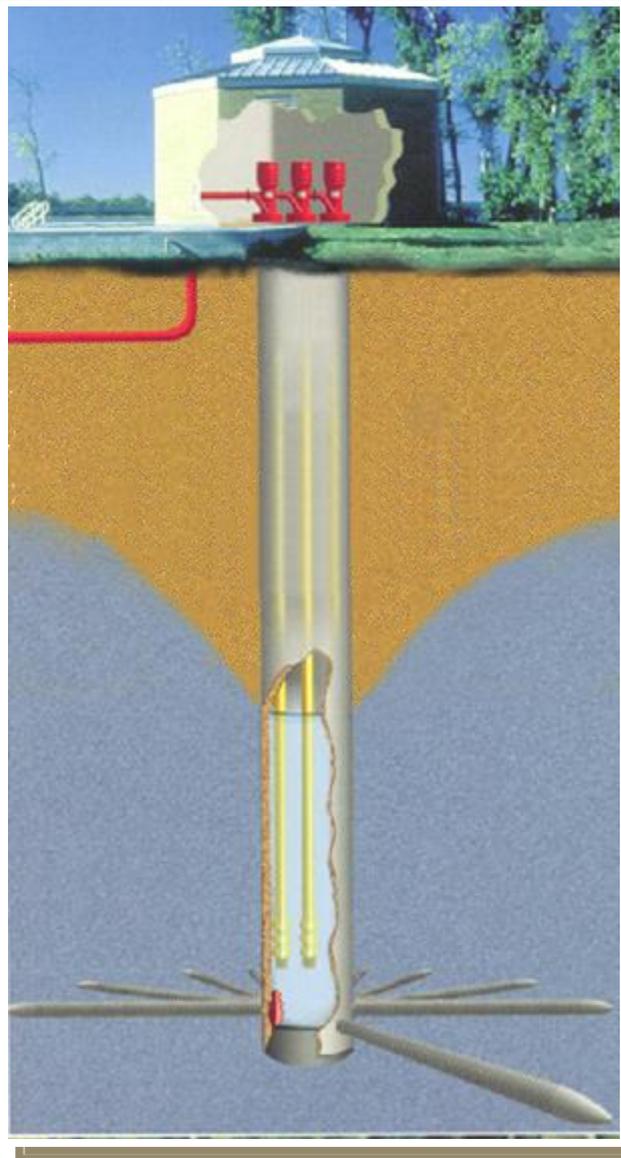
Long Beach Well Island



Horizontal Directionally-Drilled (HDD) ASR Wells

- HDD wells can access thin aquifers with over 300 m of well screen.
- Dual surface access for rehabilitation.
- Much higher potential yields than vertical wells in the same aquifer.
- Limited application to date in water supply industry. Common technology in pipeline, petroleum and hazardous waste industries.
- Netherlands: Two “Freshkeeper Wells” – Koen Zuurbier

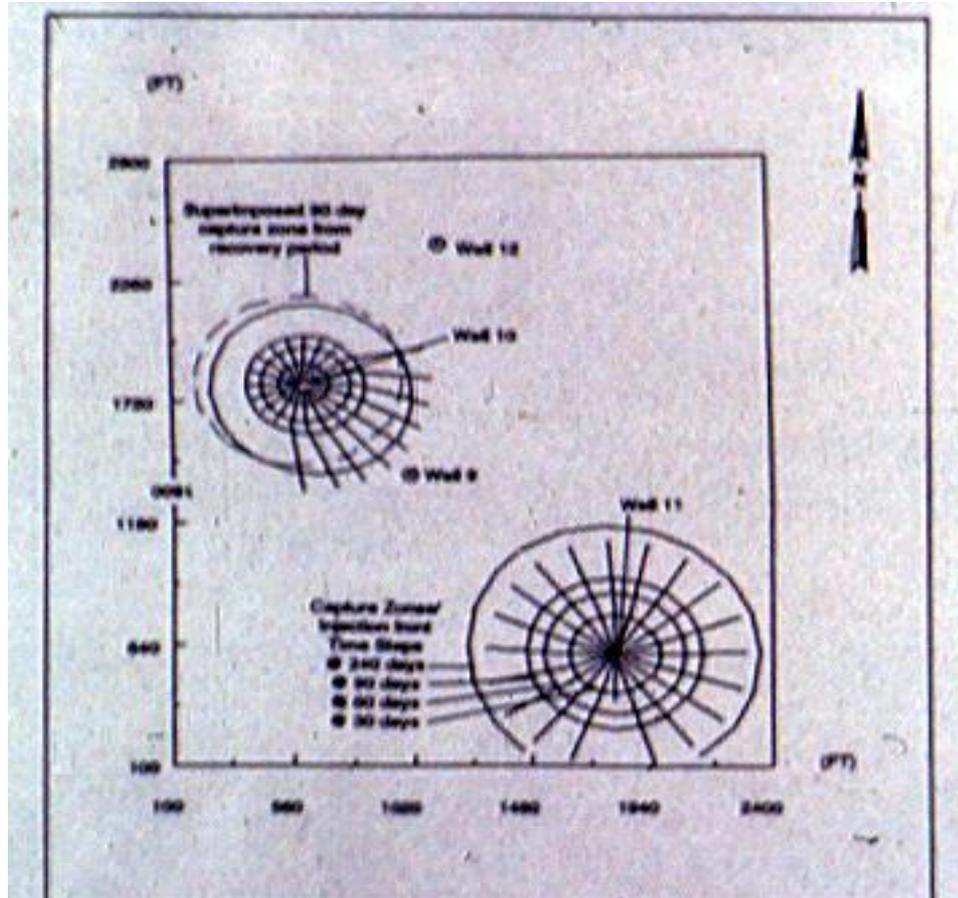




- **Central Reinforced Concrete Caisson**
- **Horizontal Well Screens**
- **Pump Station**



Wellfield interference and lateral movement of stored water is an important issue for ASR wells.



- Porosity, n
- Hydraulic Conductivity, K_h
- Gradient
- Velocity, V

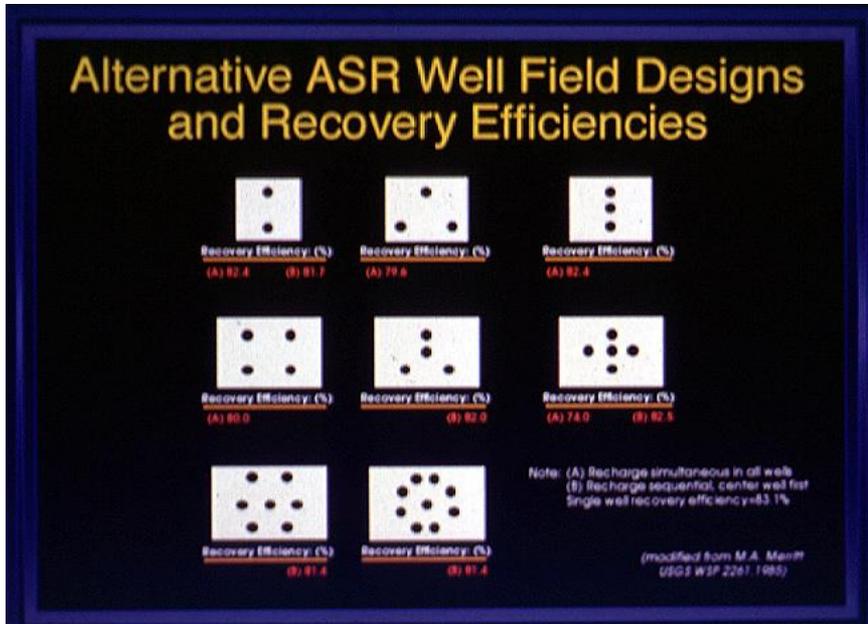
$$V = K_h \times \text{Gradient} / n$$

What is acceptable regional lateral velocity for an ASR well?

- feet/year?
- Tens of feet/year?
- Hundreds of feet/year?
- Important?
- Unimportant?



Alternative ASR Wellfield Designs, Operations and Recovery Efficiencies



Initiate recharge at a central well

Add recharge to surrounding wells as the recharge front passes those wells, thereby flushing ambient groundwater away from the center of the wellfield. Reverse the sequence during recovery

Operate separate well clusters in an ASR wellfield to achieve recovered water quality goals while conserving remaining stored water

Orient wells for lateral movement so that water lost from upgradient wells can be recovered from downgradient wells

Well interference

Well spacing is usually closer than for conventional production wellfields



Other ASR Operational Considerations

- Availability and suitability of well sites
- Retrofit of existing wells vs new wells
- Proximity of transmission/distribution pipelines and their conveyance capacity during recharge/recovery
- Disposal of water during testing and operations
- Recharge water quality and variability
- Inventory of nearby wells, owners, depths, uses, basements that could flood if water levels rise
- Monitoring requirements, data evaluation and reporting
- Instrumentation and control system (SCADA) capabilities
- Wellfield Protection Area (WPA) to protect stored water volume and quality
- Mitigation measures for offsite impacts



Potential ASR Well Locations

- Water treatment plants
- Elevated storage tanks
- Ground storage reservoirs
- Fringes of the distribution system
- Opportunities for blending, stacking
- Parks and other locations in the service area
- Outlying areas with preferred hydrogeologic suitability



Future Directions for ASR

- Regulatory frameworks that match ASR science/ technology
- Reclaimed water storage (IPR, DPR)
- Biotechnology/geochemistry advances to achieve subsurface treatment objectives
- Larger ASR programs to meet regional/national needs
- ASR wells for storage, treatment and conveyance
- Strategic Water Reserves
- Marginal cost pricing
- Thermal energy storage (ATES, BTES)
- Bank filtration/ASR combination technologies
- Desalination/ASR combination technologies (DASR)
- Horizontal Directional Drilled (HDD) ASR wells
- Well pairs and arrays to achieve storage/treatment
- Vertical stacking of storage zones
- Wellfield Protection Areas for ASR



ASR Workshop Outline

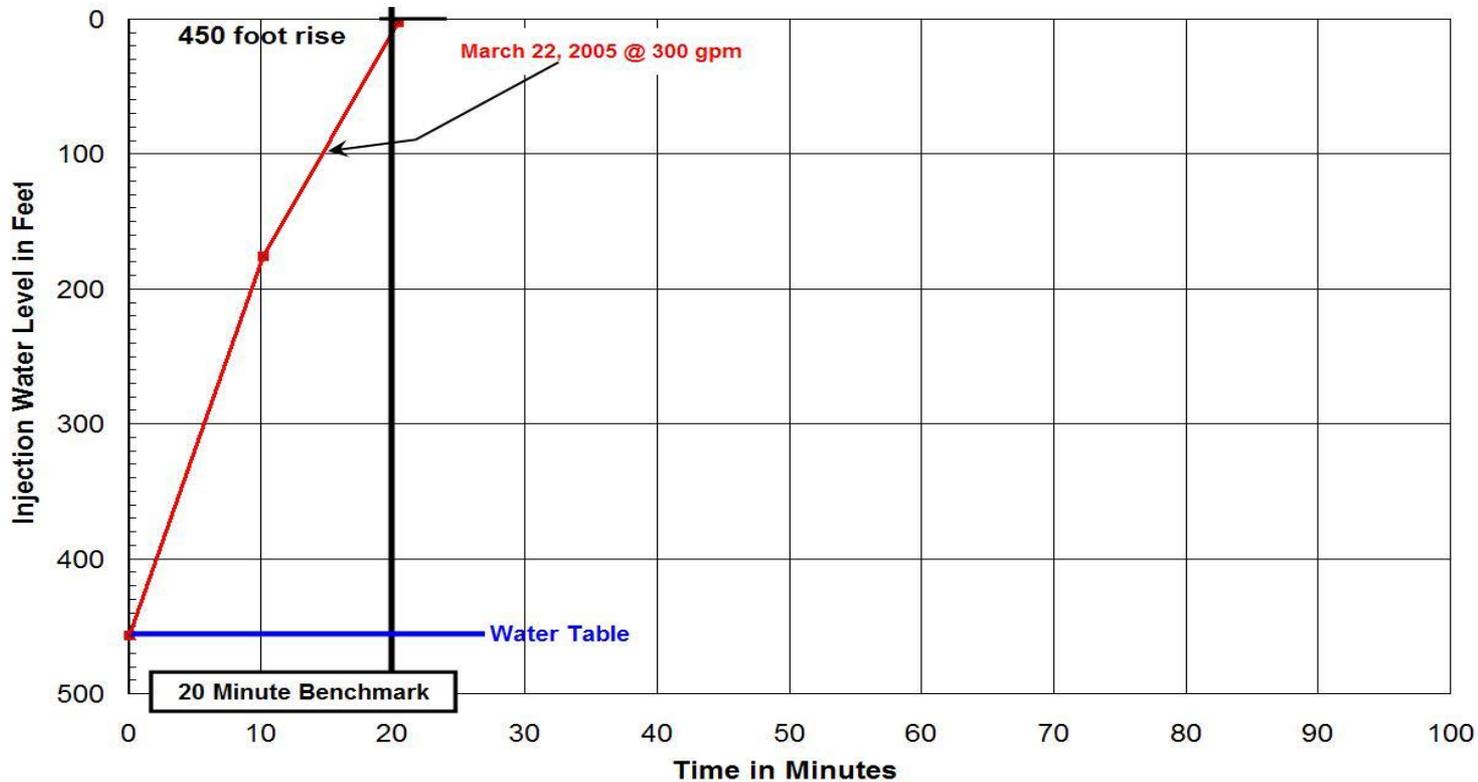
Tuesday October 6, 08:00 to 12:00

1. Introduction to Well Recharge/ASR
2. Phased Approach to Successful ASR
ASR Applications
Key Principles for Successful ASR
3. Science/ Technology
Design of ASR Wells and Wellhead Facilities
4. Well Conditioning and Operation of ASR Wells and Wellhead Facilities
5. ASR Economics/ Regulatory (optional, time permitting)



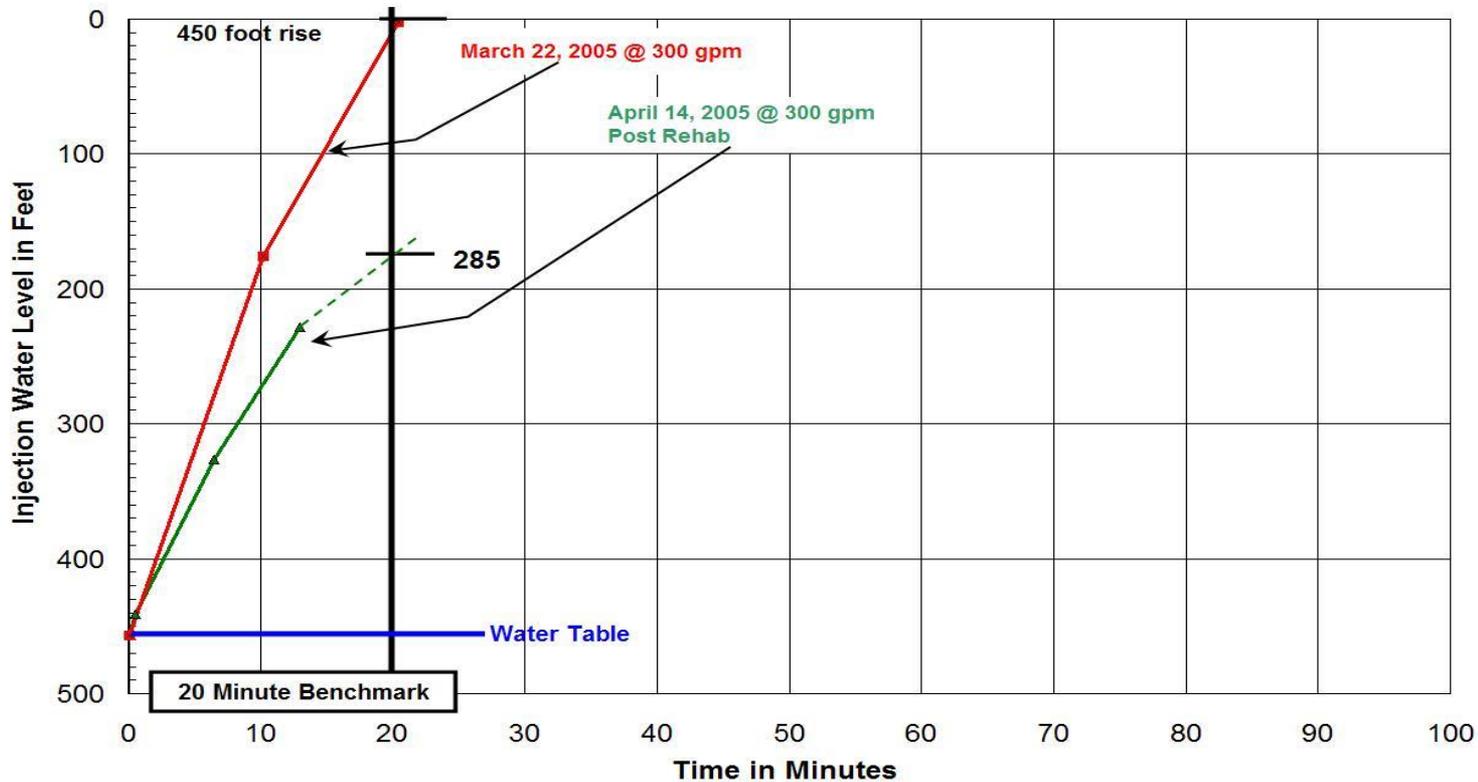
Injection Development

PFI-3 Well Development Test Trends



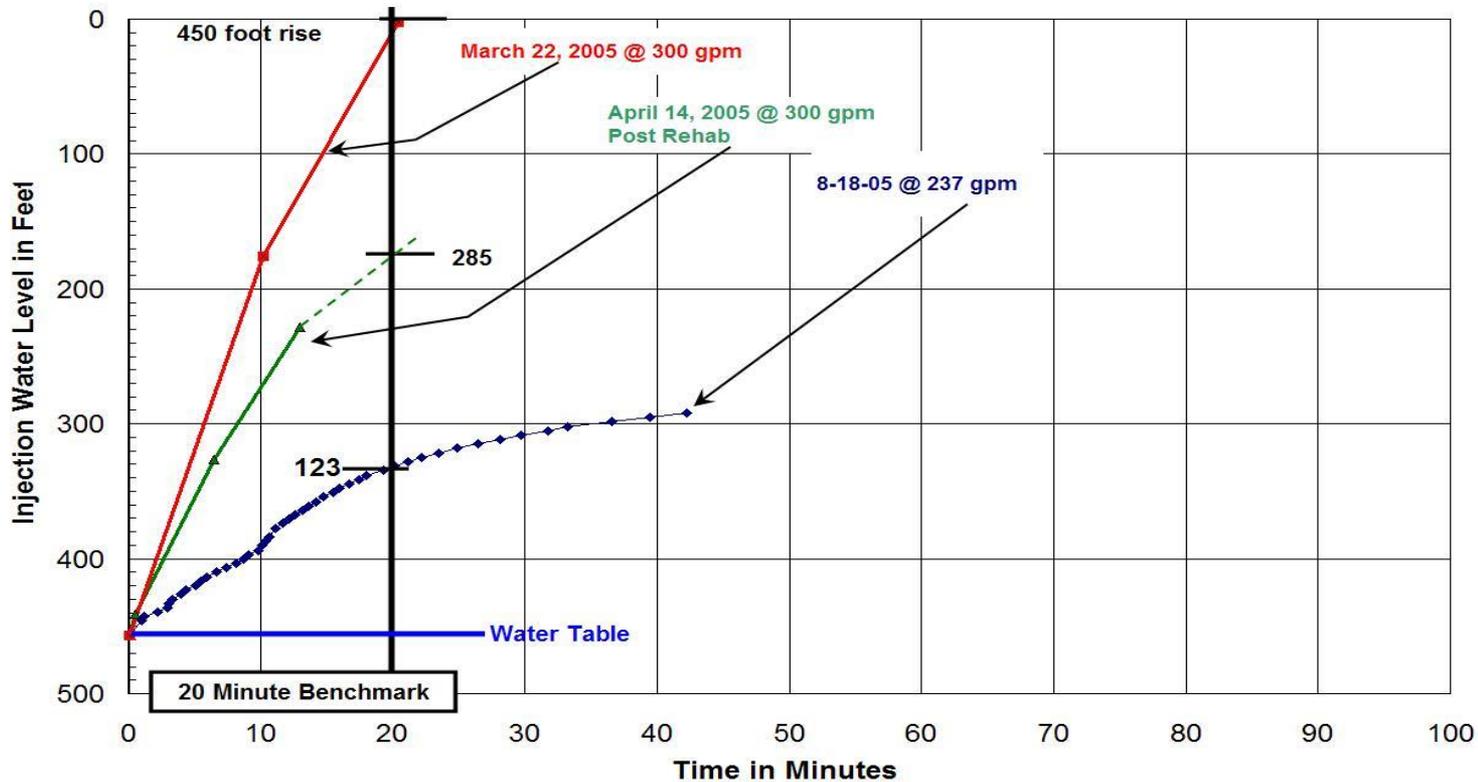
Injection Development

PFI-3 Well Development Test Trends



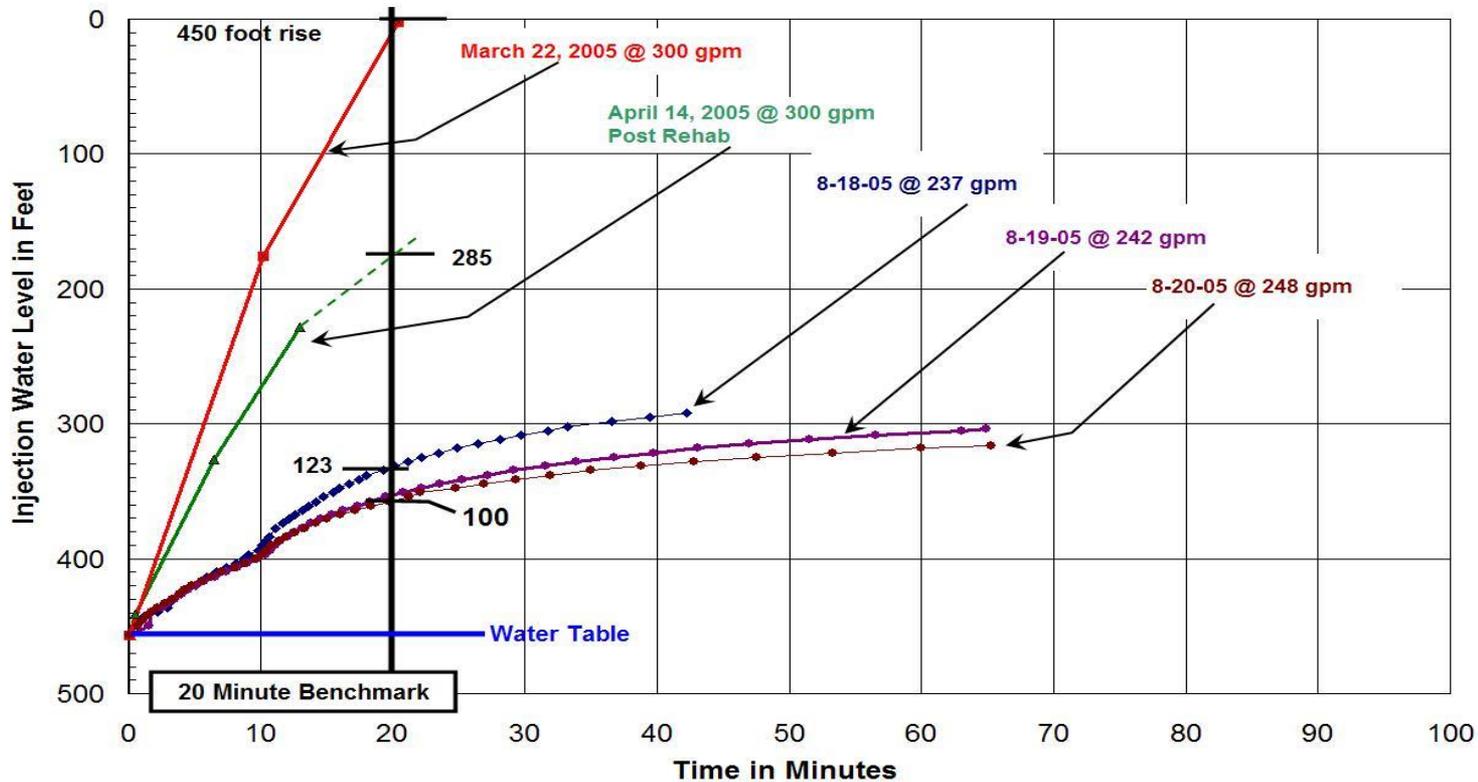
Injection Development

PFI-3 Well Development Test Trends



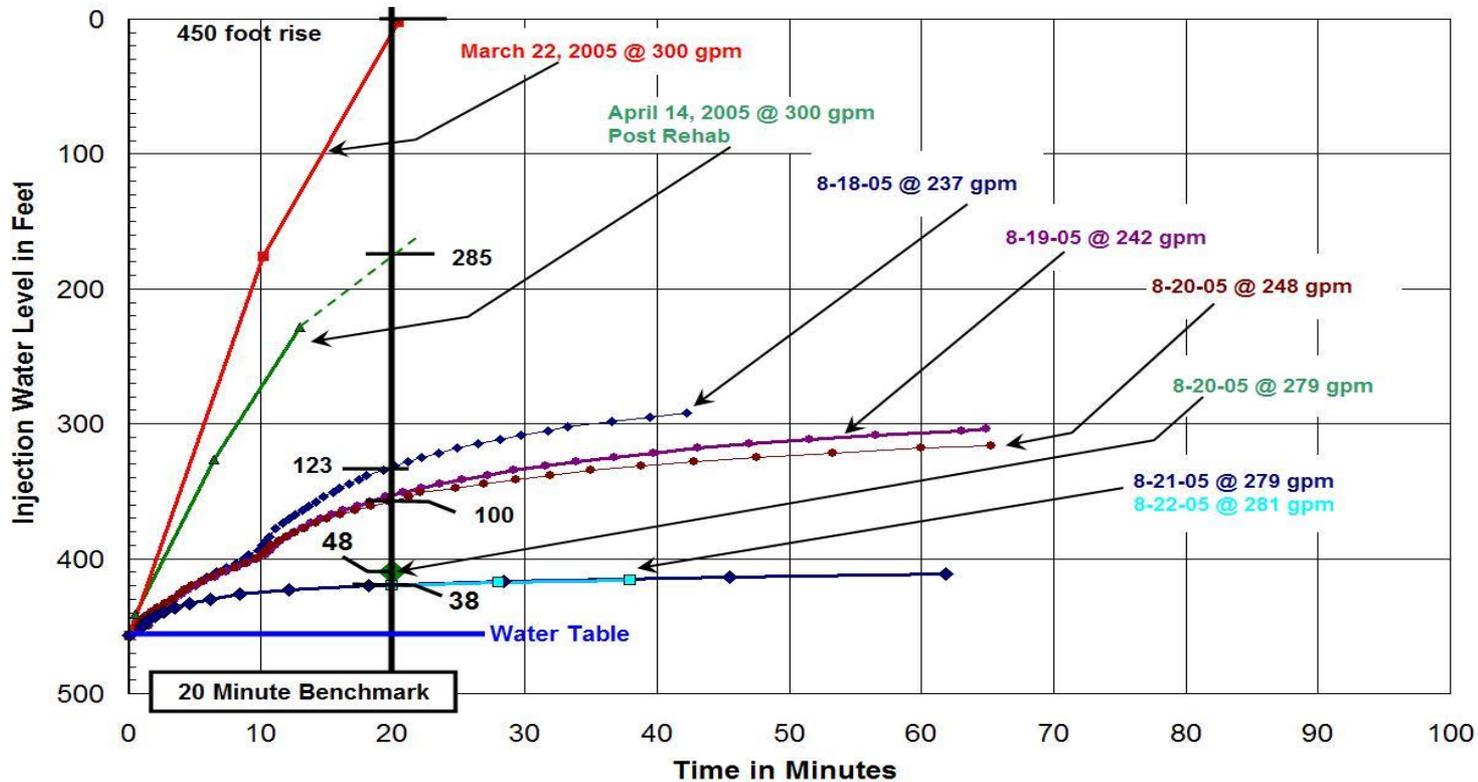
Injection Development

PFI-3 Well Development Test Trends



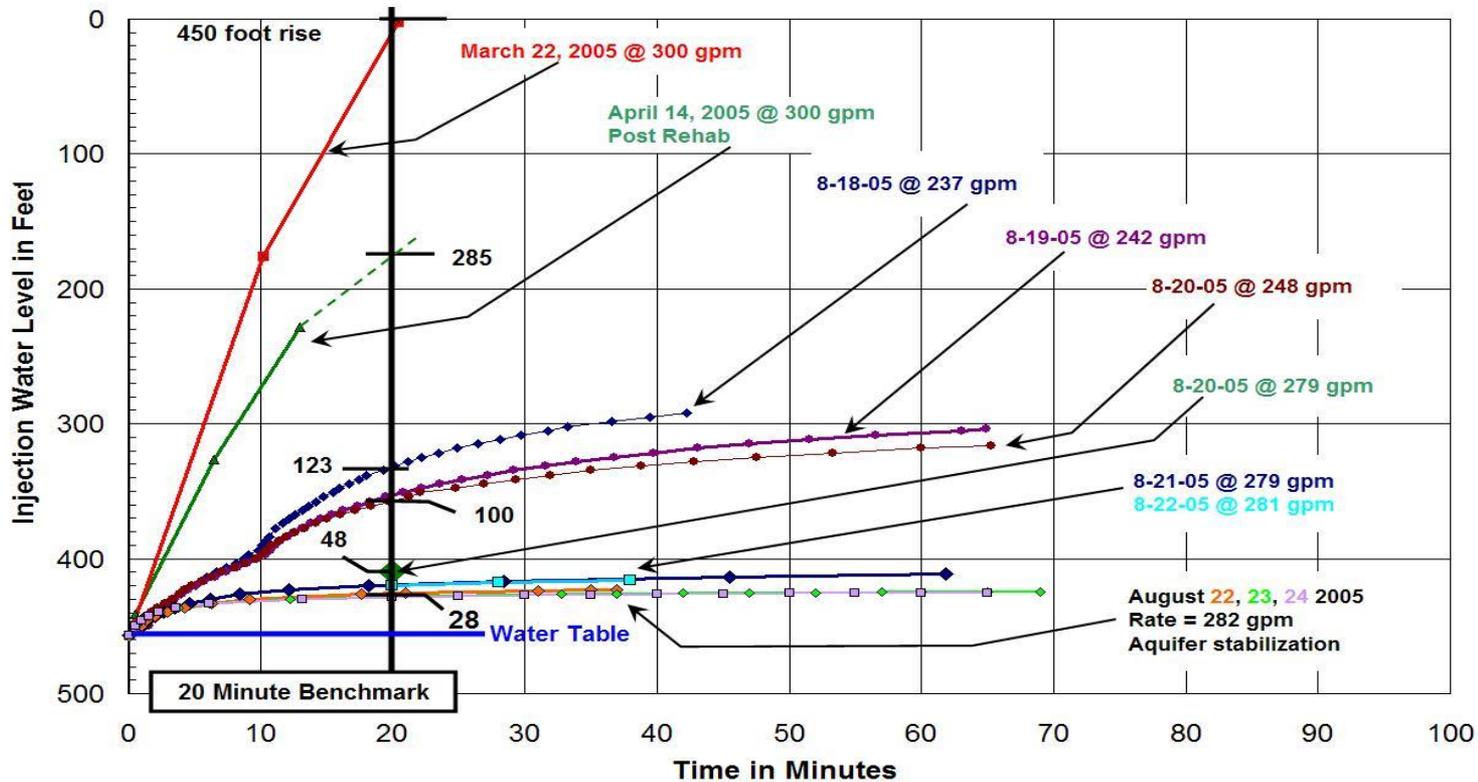
Injection Development

PFI-3 Well Development Test Trends



Injection Development

PFI-3 Well Development Test Trends



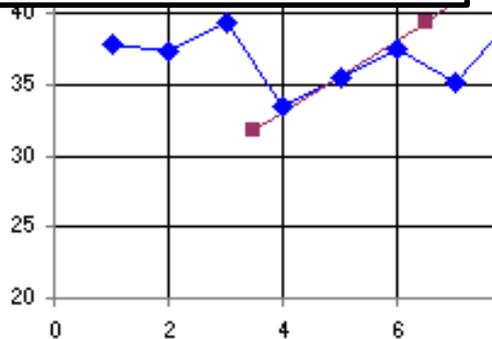
Tom Morris @ West Yost

Orangeburg DPU Well ASR-1 Development Specific Capacity Changes

Oct 2010

**15% to 55% Pump SC_p
Increase**
**25% to 300% Recharge
 SC_i Increase (450%
max)**

Specific Cap

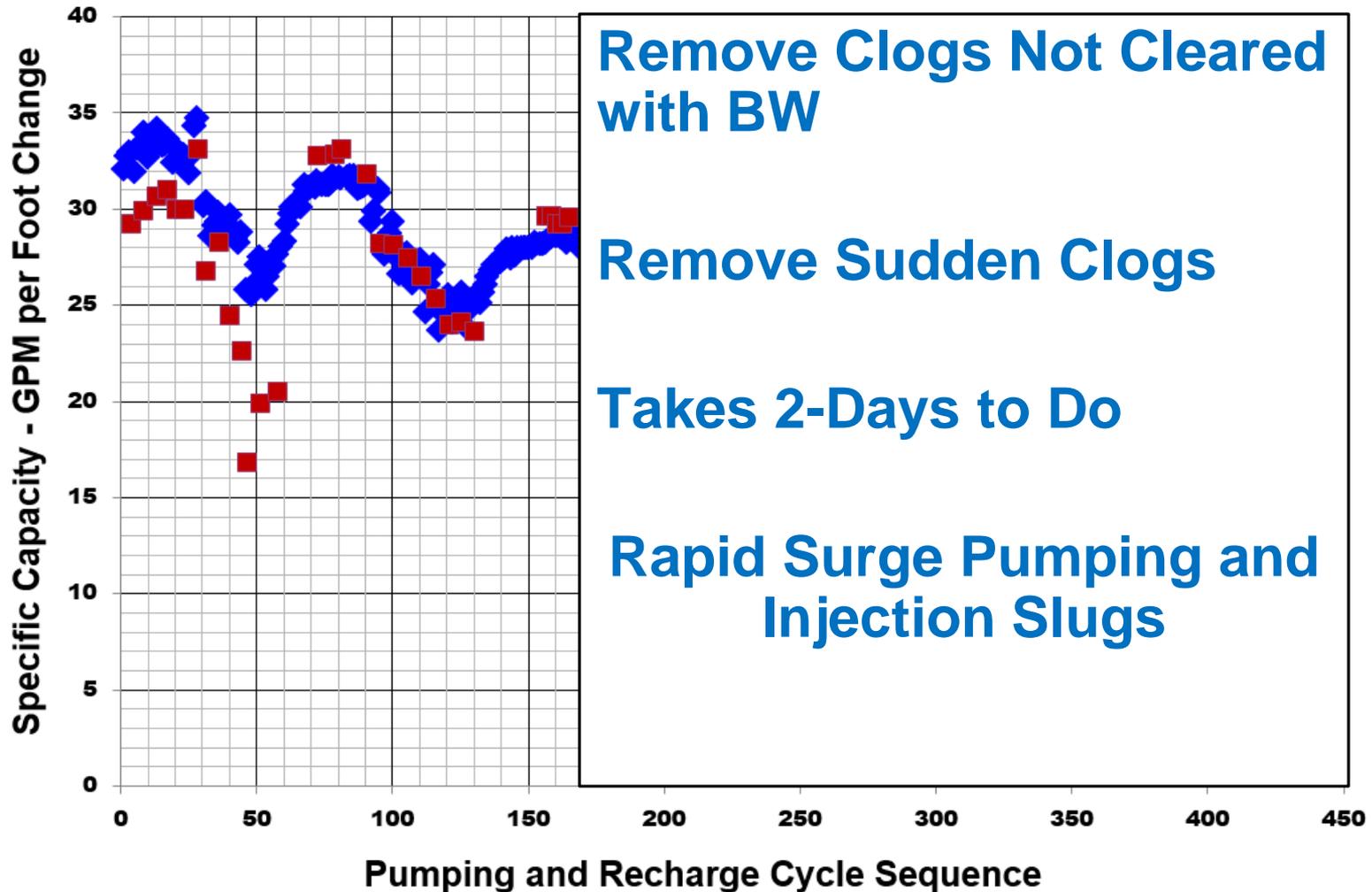


**Level 1
Radial Injection Surge Development
RISD**

Pumping and Recharge Cycle Sequence



Well Surge Conditioning Level 2 RISD



Injection Surging Level 3 RISD



Common Pump Surge
Limited Impact Distance

Injection Pump Surge
**Water Added to Increase
Impact Distance**

Can
Clean Select Radial Rings
**Up to 16 inches from
Screen**



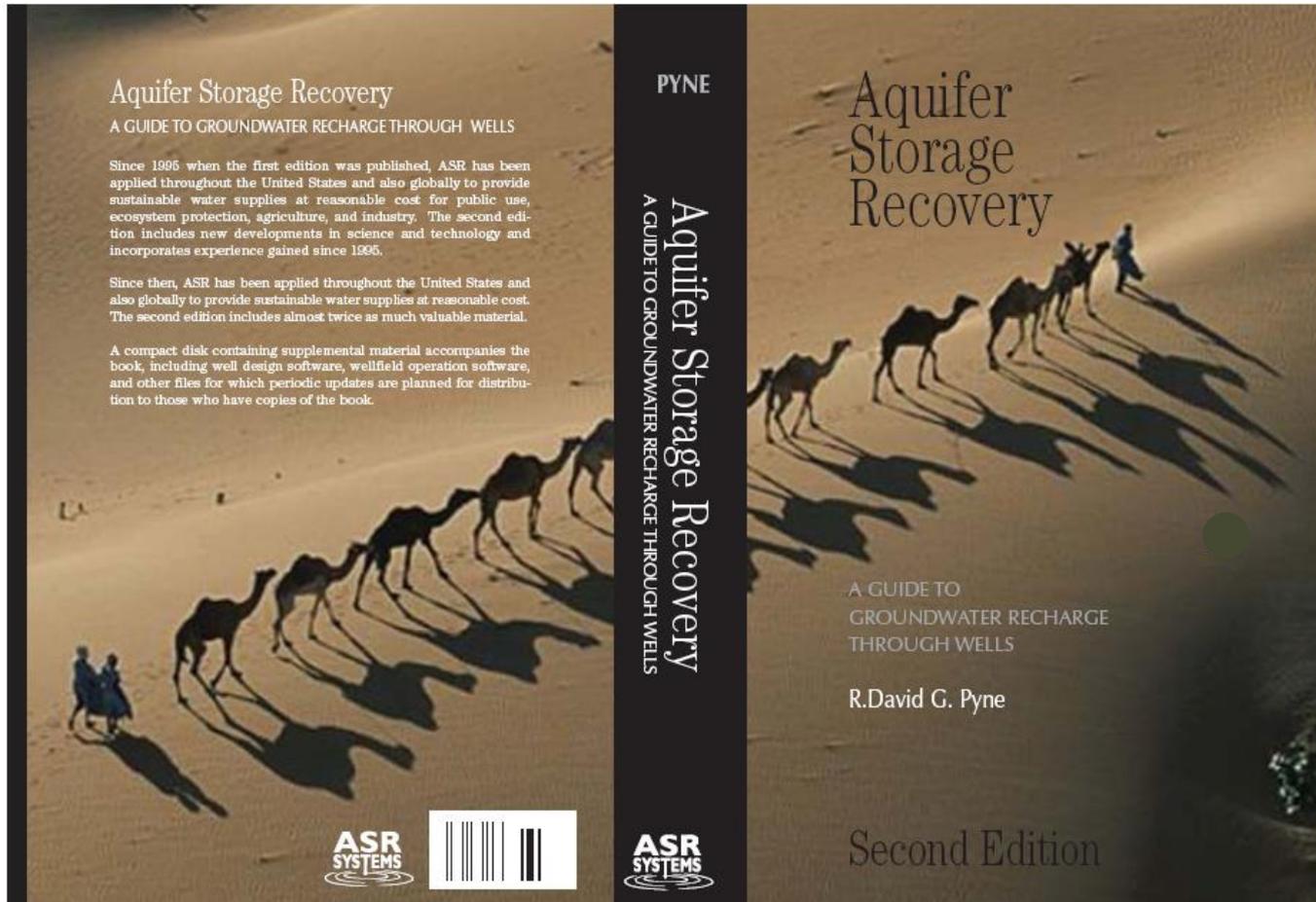
ASR Operations Data Collection & Review

- Local / remote control & data storage; historian
- Excel format for data recording, summary and graphical presentation
- O&M Manual (draft and final)
- Training program (classroom and onsite)
- Initial startup monitoring and adjustments to flows, pressures, set points, time delays, dead-bands, password-protection levels, etc during first 2 to 3 months
- Annual performance review and adjustments



ASR Book, Second Edition

www.asrforum.com



Or purchase from NGWA



Housekeeping Details

- Questions and Answering Process
 - Anytime via brief “chat” text message
 - Responses between each of the five “sessions” and at end of presentation
- Ten-minute break in middle
- Email to dpyne@asrsystems.ws if you need certification for 4 hours of CEU credits and did not note that on the conference registration form.
- Stop at 4 hours. Last segment on ASR Economics is flexible and content will depend on available remaining time, plus final Q&A



ASR Workshop Outline

Tuesday October 6, 08:00 to 12:00

1. Introduction to Well Recharge/ASR
2. Phased Approach to Successful ASR
ASR Applications
Key Principles for Successful ASR
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Definition of ASR for Economic Analysis Purposes

- **Included:**
 - Storage of water in a well during times when water is available for storage, and recovery from the same well when the water is needed
 - Construction, equipping and operation of ASR wells and wellfield piping, and associated disinfection facilities for treatment of recovered water
 - Any supplemental pretreatment of recharge water or post-treatment of recovered water that may be required
- **Not included:**
 - Long-distance transmission of water to and from the ASR wellfield
 - Treatment plant construction and operation not required for ASR recharge or recovery



*Highlands Ranch, Colorado
One of 26 ASR wells, mostly
in vaults*



ASR Unit Capital Costs – about US\$1.00 per gallon per day of recovery capacity

- Capital costs include construction plus engineering, legal, fiscal and administrative costs.
- South Florida WMD ASR Economics Analysis
 - June 2006 survey of ASR unit capital costs (construction + engineering) from 11 ASR wellfields in Florida
 - **Average unit construction cost of \$1.00 per gallon per day of recovery capacity, within approximate range of \$0.50 to \$2.00/gpd**
 - Lower unit costs with high yield wells, multiple wells, shallow wells.
 - Higher unit costs with low yield wells, individual wells, deep wells
- San Antonio Water System (2004 – 2006)
 - Wellfield, land, mitigation, 25% of overhead costs -- **\$1.13/gpd**
- Subsequent unit capital costs (2012 to 2013)
 - Orangeburg Department of Public Utilities, Orangeburg SC
 - Hilton Head Public Service District, Hilton Head SC
 - Cape Fear Public Utility Authority, Wilmington NC
 - South Island Public Service District, Hilton Head SC
 - **Average \$1.02/gpd; Range \$0.77 to \$1.55/gpd**



Capital Cost Comparisons

<u>Source/Storage Option</u>	<u>Typical \$/GPD Capacity</u>
Conventional Supply	0.50 – 5.00
ASR	0.50 - 2.00
Brackish Desalination	2.00 – 5.00
Seawater Desalination	7.00 – 12.00
Surface Reservoirs	3.00 – 30.00
Indirect Potable Reuse	7.00 – 25.00

ASR is complementary to other sources, increasing total yield and reliability. With adequate ASR capacity, 100% reliability can be achieved at reasonable capital cost.



ASR Unit Operating Costs

- Limited available data on ASR wellfield operating costs, independent of water sources, water treatment, transmission and administration costs which are often combined.
- 2005 ASR Book (Second Edition) –
 - Average \$15,000/yr/ MGD recovery capacity
 - Range \$6,000 to \$40,000
- SFWMD 2006 Survey of 4 Florida ASR wellfields
 - Average: \$106,000 per year per MGD of recovery capacity
 - Range: \$61,000 to \$173,000
 - Reflects very high monitoring costs during initial cycle testing at all four sites, required by FDEP. Lower long term costs expected.
- 2020 best estimate is US\$40,000/yr/MGD recovery capacity, (pumping, monitoring, reporting, maintenance)



Operating Cost Units...Cost/Unit Rate or Cost/Unit Volume (\$/yr/MGD or \$/MG)?

- Need to consider **both** units in any ASR economic evaluation, whether comparing ASR sites or alternative supplies
- Wildwood, New Jersey - ASR since 1969
 - ASR for summer peaking (July 4 weekend) and also for prevention of saltwater intrusion into coastal aquifer
 - Total annual volume recovered is small (≈ 320 MG)
 - Unit cost/yr/MGD capacity is very low
 - Unit cost/MG recovered is very high
 - Alternative peaking supplies far more expensive
- San Antonio, Texas - ASR since 2004
 - ASR for long term storage and also for seasonal peaking
 - Total volume recovered during Drought of Record would be large
 - \$85,000/yr/MGD capacity is about average; \$/MG highly variable, depending on volume recovered in any year.
- Victoria, Texas - Cost per AFY for “firming up” water supply reliability - \$192/AFY



Estimated ASR System Costs - Victoria

- Phase 2 Testing Program: \$3.6 million
- Total Capital Cost: \$14.5 million
- Total Project Cost: \$21.1 million
- Total Annual Cost: \$ 1.5 million (debt service + O&M)
- ASR Project Unit Cost: \$56 per AFY (\$0.17 /K gal)
- Incremental cost of treatment/storage: \$ 136 per AFY (\$0.42/k gal)
- Total Unit Cost: **\$192 per AFY** (\$0.59/K gal)



Marginal cost water pricing is potentially a powerful water management tool...

- Seasonal storage programs
 - New Jersey American Water Company
 - Beaufort-Jasper Water & Sewer Authority and Hilton Head Public Service District, SC
 - (Metropolitan Water District of Southern California)
- Supply water at reduced cost to major customers during offpeak periods
- Pay for seasonal storage (ASR) with cost savings
- Typical water utility marginal cost for chemicals, electricity and residuals disposal during offpeak periods is about US\$0.15 to \$0.35/kgal



Water Storage Leasing

- \$/year per unit of storage volume leased
- Lessor would have favorable hydrogeologic conditions for ASR storage of large volumes underground, more than they need. Lessee would have water that it needs to store, but unsuitable local hydrogeologic conditions.
- Concept was originally developed at Pasadena through negotiations with the Metropolitan Water District of Southern California, to replace their Seasonal Storage Program.
- Possible application for other areas with suitable hydrogeology and legal framework



Legal, Regulatory, Institutional Considerations

- A reasonable legal framework is needed for groundwater management to achieve effective control over water stored underground and/or transported to where it is needed, when it is needed
- Water quality required for recharge and for recovery
- Point of compliance measurement
- Seasonal vs. Long term storage
- Land ownership or control
- Balancing of risks, benefits and costs
- A suggested ASR regulatory framework is proposed in Section 6.4 of ASR book



Where to measure compliance with water quality standards during ASR recovery?

- **At the ASR wellhead after disinfection?**
 - Applies to single ASR well installations with no opportunity for blending
 - Less common
- **At the point where recovered water leaves the treatment plant or the ASR wellfield and enters the distribution system?**
 - Provides excellent opportunity for blending and internal wellfield management while meeting water quality criteria for the wellfield product water
 - Common practice at most ASR wellfields
- **Internal to the distribution system after blending from one or more other sources**



Where to measure compliance with water quality standards during ASR recharge?

- **At the ASR wellhead?**
 - Possible need for pre-treatment to prevent As mobilization, DBP formation or other potential aquifer contamination
 - Requires pretreatment for disinfection byproduct reduction (DBPs); microbiota (coliforms) and nitrites prior to storage of reclaimed or surface water (possibly also color)
- **At a monitor well?**
 - Provides for natural treatment close to the ASR well
 - Current USEPA policy
 - Also followed in Australia and Netherlands
- **Point of Compliance measurement may be critical to ASR viability and cost-effectiveness**



Multiple barriers protect ecosystems, public health and groundwater quality with ASR storage.

- Water treatment before recharge
- Any blending of the recovered water
- Small radius of the stored water bubble
- Essentially full recovery of the stored water
- Natural treatment processes occurring in the aquifer, including dilution
- Any treatment of water recovered from any surrounding potable supply wells
- Ability to pump stored water from ASR well
- Successful similar experience elsewhere

**Need to balance risks,
benefits and costs.**



Looking back...and to the future

- Four National Award-winning ASR projects from American Council of Engineering Companies (ACEC):

- Manatee County, Florida 1984
- City of Kerrville, Texas 1992
- City of Oak Creek, Wisconsin 2001
- City of Woodland, California 2019

Woodland CA _ ASR Well 29



- ASR projects of particular interest:

Westlands Water District, CA (*Ag ASR*)
Oxnard, CA (*IPR ASR*)

- **Others???**

Lake Okeechobee, FL
(*Environmental ASR*)



ASR: An Oasis for a Thirsty World

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