WATER QUALITY REVIEW AND ASSESSMENT:
BORREGO WATER DISTRICT (BWD) WATER SUPPLY WELLS

OVERVIEW

The purpose of this Report is to review water quality data for active Borrego Water District (BWD) water supply production wells to

1) Provide an overview of water quality conditions among the wells and assess spatial variations;
2) Examine how water quality has changed over time due to overdraft;
3) Evaluate the potential relationships among multiple water quality parameters as a means to support trend analyses for the five primary chemicals of concern (COCs) that include arsenic, total dissolved solids (TDS), nitrate, sulfate, and fluoride (As, TDS, NO_3, SO_4, and F);
4) Determine how well water quality trends may (or may not) be able to be identified among BWD water supply wells; and,

The Borrego Springs Subbasin (Subbasin) of the Borrego Valley Groundwater Basin is in a state of critical overdraft and subject to the Sustainable Groundwater Management Act (SGMA). As defined under SGMA[1] "A basin is subject to critical overdraft when continuation of present water management practices would probably result in significant adverse overdraft-related environmental, social, or economic impacts."

Pursuant to SGMA a Groundwater Sustainability Plan (GSP) is currently under development for the Subbasin. This work updates and extends beyond prior work done by Dudek to assess water quality trends for BWD wells as described in the Draft Borrego Springs Subbasin Groundwater Quality Risk Assessment presented to the BWD Board on 6/28/2017.[2]

The analyses included herein will be used in subsequent ENSI reports to examine potential BWD water supply impacts and costs associated with current and future water quality conditions.

[1] See: https://water.ca.gov/Programs/Groundwater-Management/Bulletin-118/Critically-Overdrafted-Basins
[2] The data used in the Report were located and compiled by Dudek staff as part of the GSP preparation process. The analyses presented in this Report would not have been possible without their support.

Preparation of the GSP is underway and it is understood that the draft GSP will be available for public review by January 2019[3]. The GSP will include a range of potential options for Projects and Managements Actions (PMAs), including PMAs to address water quality and water quality optimization. Among the direct impacts of degraded groundwater quality to BWD include:

- Need for Water Treatment to achieve drinking water standards (on a per well basis)
- Impact of water quality on the choice and design of replacement wells at existing well locations
- Potential need for Intra-Subbasin Transfer of Potable water from new or existing wells due to degraded water quality due to natural or anthropogenic sources

Groundwater quality data also have a role in the assessment of potential water management options that include but are not limited to:

- Options for Enhanced Natural Recharge (understood to be limited)[4]
- Artificial Recharge using Treated Wastewater

Of primary concern to BWD is the ability of historical data combined with ongoing water quality monitoring program to assess water quality trends. The data are needed to support management of their water system, for example to assess the probability of MCL (maximum contaminant level) exceedances and to plan for water treatment, if needed.

[3] The GSP is being developed by the Groundwater Sustainability Agency (GSA) that consists of the County of San Diego and the Borrego Water District. See overview at: https://www.sandiegocounty.gov/pds/SGMA.html

[4] It is understood that that recharge basins within the floodplains where much of Borrego Springs' residential population is located are likely not permittable due to County Flood Control Management concerns. Similarly managed artificial recharge areas located along mountain fronts within or nearby to the Anza Borrego State Park are also not likely permittable given their potential impact on the State Park.

This report includes the following sections:

1.0 HYDROLOGIC CONDITIONS

A brief summary of the hydrologic conditions of the Subbasin is provided here to support review of the water chemistry data. Included is a description of groundwater recharge, pre- and post-development groundwater levels, and aquifer conditions. Many of the figures and much of the discussion included in this section was derived from the USGS Model Report prepared in 2015 entitled *Hydrogeology, hydrologic effects of development, and simulation of groundwater flow in the Borrego Valley, San Diego County, California*: U.S. Geological Survey Scientific Investigations Report 2015–5150[5]. For reference the *simulation of groundwater flow* refers to the use of a numerical model (in this case the USGS Modflow Model as described in the 2015 report) to examine the groundwater levels, recharge, and overall hydrologic conditions for the period of 1945 to 2010. The GSP contains additional detailed hydrologic information, and updates the USGS modeling work.

1.1 Basin Location and Setting: Contributory Watersheds

The Borrego Springs Subbasin (Subbasin) of the Borrego Valley Groundwater Basin is located at the western-most extent of the Sonoran Desert. The primary source of water to the Subbasin is surface water (storm water and ephemeral stream flow) that flows into the valley from adjacent mountain watersheds and infiltrates within the valley. The contributory watersheds are approximately 400 square miles (mi^2) and much larger in area than the approximately 98mi^2 Subbasin as illustrated in **Figure 1**.

Direct recharge by rainfall within the valley is very low compared to surface water inflows as the annual rainfall averages 5.8 inches per year (in/yr.) [USGS Model Report, page 43]. Stream and flood flows from the adjacent watersheds provide the bulk of the water that enters the Subbasin.

[5] Referenced herein as the "USGS Model Report": Faunt, C.C., Stamos, C.L., Flint, L.E., Wright, M.T., Burgess, M.K., Sneed, Michelle, Brandt, Justin, Martin, Peter, and Coes, A.L., 2015, Hydrogeology, hydrologic effects of development, and simulation of groundwater flow in the Borrego Valley, San Diego County, California: U.S. Geological Survey Scientific Investigations Report 2015–5150, 135 p.
See: http://dx.doi.org/10.3133/sir20155150

FIGURE 1 (from USGS Model Report)

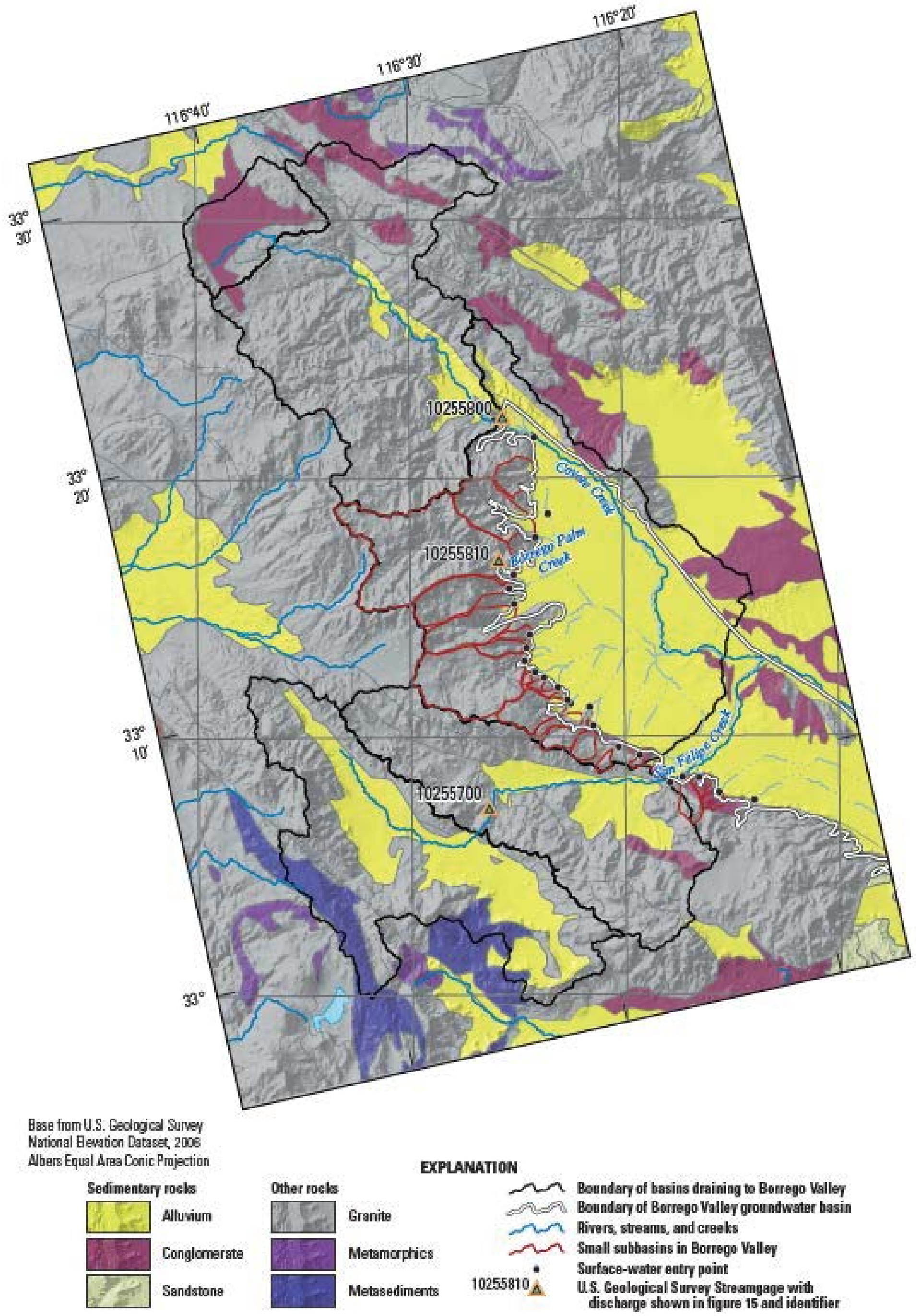


Figure 16. Drainage basin boundaries and geology used in the Basin Characterization Model to estimate climate-driven natural recharge in the Borrego Valley, California.

Note: The Subbasin lies within the area defined by alluvium. The tributary watersheds (e.g. that support Coyote Creek, Borrego Palm Creek, and San Felipe Creek) are outside of the Subbasin.

1.2 Historical Groundwater Conditions

The Subbasin receives recharge waters from the adjacent watersheds that include Coyote Creek, watersheds along the northwestern edge of the valley such as Borrego Palm Canyon, and San Felipe Creek that enters the south side of the valley (**Figure 1**).

Two water level maps from the USGS Model Report are included in **Figures 2A** and **2B** that depict pre- and post- development water levels (1945 and 2010). In both cases the Subbasin can be generally described as “closed” where surface water flows typically do not discharge from the valley but instead, if sufficient flows occur, terminate at the Borrego Sink.

Prior to development (**Figure 2A**) groundwater flow within the northern and central portions of the valley can generally be described as moving from northwest to southeast towards the Borrego Sink. Flow in the southern portion of the Subbasin is directed northeast towards the Borrego Sink. Pumping since 1945 has lowered groundwater levels and led the development of significant depressions of the water table associated with ‘pumping centers’ (see **Figure 2B**). From a groundwater perspective the overall flow patterns in the northern and central areas of the valley have changed from a roughly uniform flow (generally towards the Borrego Sink) to a condition where groundwater flow is reversed in some areas and now flows toward the pumping centers. The rate of pumping has greatly exceeded groundwater recharge rates and water levels have dropped well over 100 feet in some areas. Because the current rate of groundwater use continues to cause significant water level decline and loss of water from subsurface storage the Subbasin is now classified as being in critical overdraft.

Further description of historical and current groundwater conditions is included in the GSP.

FIGURE 2A (from USGS Model Report)

44 Hydrogeology, Hydrologic Effects of Development, and Simulation of Groundwater Flow in the Borrego Valley

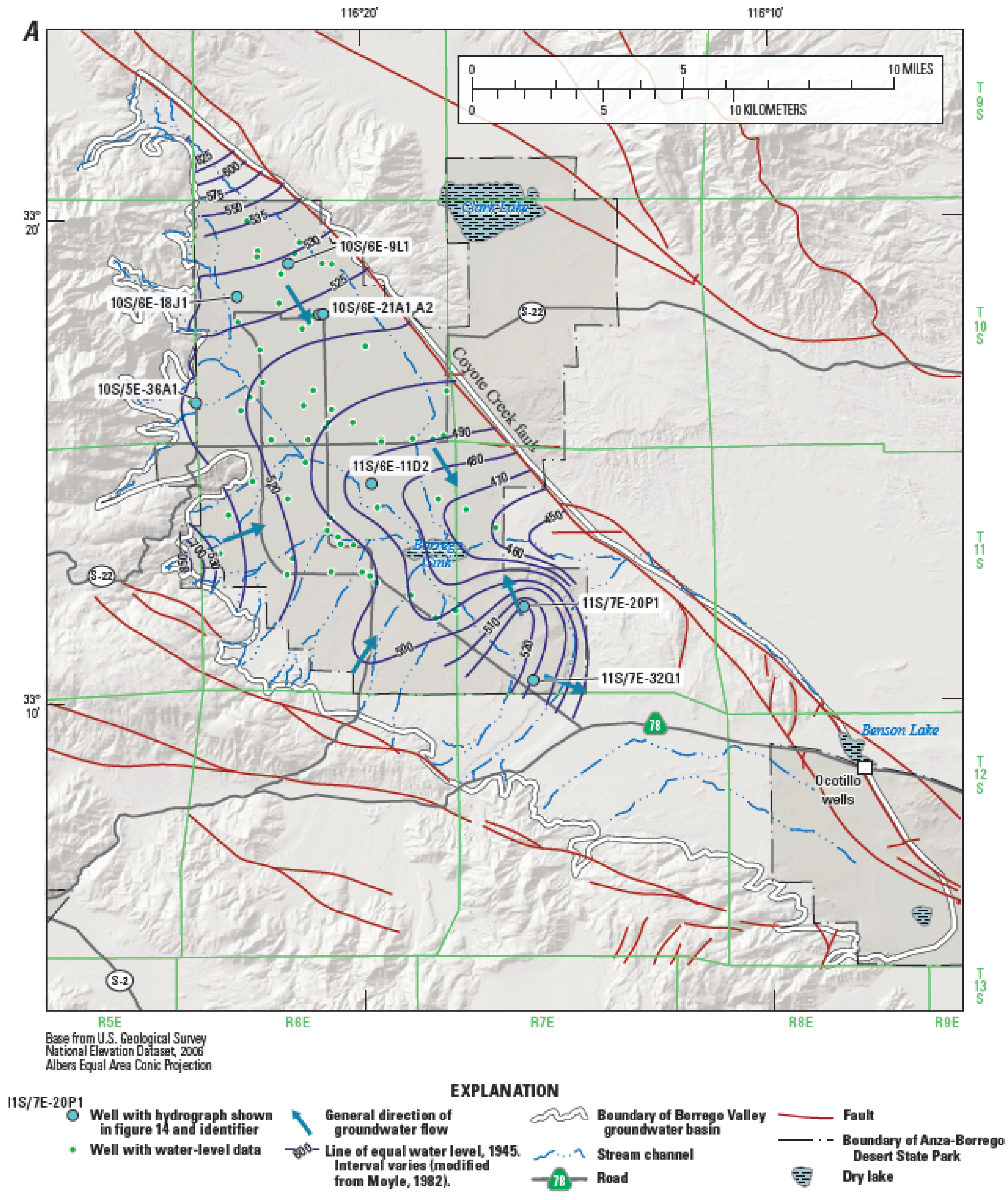


Figure 13. Water-level elevations and direction of groundwater flow in Borrego Valley, California, for *A*, 1945, approximately predevelopment, and *B*, 2010. (2010 data are modified from http://www.dpla.water.ca.gov/sd/groundwater/basin_assessment/basin_asssment.html).

Note: The arrows indicating groundwater flow are roughly coincident with intermittent surface water channels (dashed blue lines) that enter from adjacent watersheds and flow towards the Borrego Sink.

FIGURE 2B (from USGS Model Report)

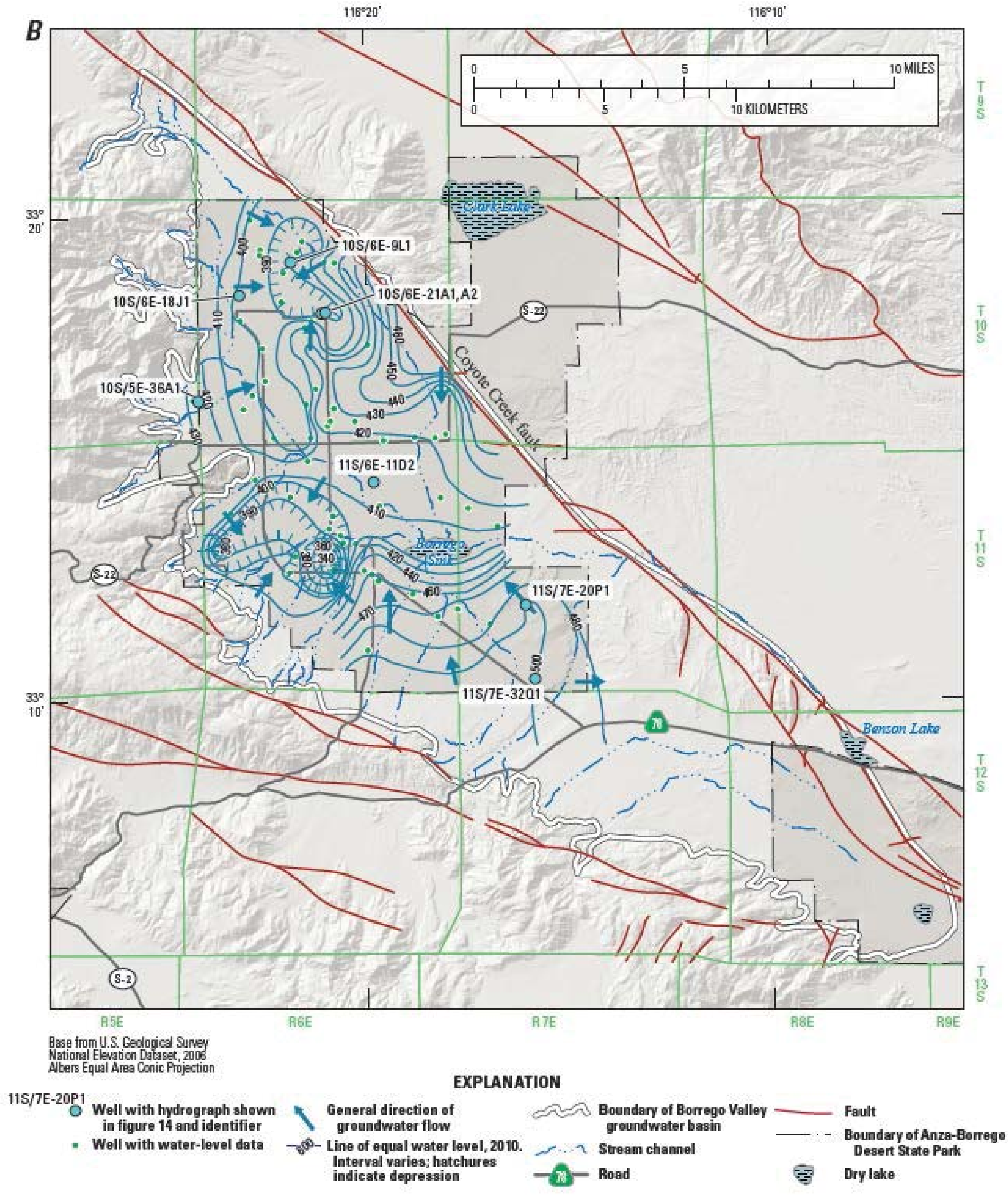


Figure 13. —Continued

NOTE: Hachured areas show the two major pumping centers in the Subbasin. The influence of northern pumping center has caused groundwater to reverse flow direction (see arrow at well 10S/6E-21A1). The central pumping center captures groundwater that was previously flowing south and southeastward towards the Borrego Sink.

1.3 Stratigraphy and Aquifer Conceptual Model

The current conceptual model for the aquifer system as incorporated in the USGS Model is that it consists of three unconfined aquifers named the upper, middle and lower aquifers. The upper and middle aquifers are the primary sources of water currently and are typically comprised of unconsolidated sediments. However, with time, the upper aquifer has become or is expected to become dewatered and the lower aquifer will become a more important source of water as overdraft continues.

The lower aquifer sediments become consolidated with depth and have been subject to folding and faulting. The lower aquifer provides water supply for some pumpers, especially in the southern area of the Subbasin. **Figure 3** (Figure 7 of the USGS Model Report) depicts the Borrego Valley Groundwater Basin as described by Moyle, 1982.[6] Additional work has been done by Mitten et al (1989),[7] and by Netto (2001).[8] Of these, Netto (2001) provides the most detailed analysis of basin stratigraphy based on well log review and interpretation. Review of their work supports that locally confined aquifer conditions are expected to occur.

In brief there are a number of geologic features relevant to groundwater conditions and water quality:

- The Subbasin, as exemplified by the flow of water and sediment toward the current-day Borrego Sink, has historically been the locus of sediment deposition. Sedimentation initially occurred in a marine environment (with sediment sources located to the east) and transitioned to terrestrial environments as seen today.[9]
- The Borrego Sink, similar to dry lake beds that occur in the desert, is a location where water evaporates and minerals will accumulate and can form evaporite deposits. Historically similar conditions occurred as sediments were deposited. Thus, the middle and upper aquifers have the potential to include evaporite deposits that can re-dissolve and lead to elevated concentrations of sulfates and carbonates that result in corresponding increase in TDS.

[6] Moyle, W. R., 1982, Water resources of Borrego Valley and vicinity, California; Phase 1, Definition of geologic and hydrologic characteristics of basin: U.S. Geological Survey Open-File Report 82–855, 39 p.

[7] Mitten, H.T., Lines, G.C., Berenbrock, Charles., and Durbin, T.J., 1988, Water resources of Borrego Valley and vicinity, California, San Diego County, California; Phase 2, Development of a groundwater flow model: U.S. Geological Survey Water-Resources Investigation Report 87–4199, 27 p.

[8] Netto, S.P., 2001, Water Resources of Borrego Valley San Diego County, California: Master's Thesis, San Diego State University, 143 p.

[9] See GSP. For general reference see: Dorsey, R.J., 2005. Stratigraphy, Tectonics, and Basin Evolution in the Anza-Borrego Desert Region. In "Fossil Treasures of the Anza-Borrego Desert", George T. Jefferson and Lowell Lindsay, editors, Sunbelt Publications, San Diego California, 2006 https://pages.uoregon.edu/rdorsey/Downloads/DorseyChaperNov05.pdf

- Structural features such as the Coyote Creek Fault, the Desert Lodge anticline, and the effect of basement uplift and exposure of lower aquifer sediments along the southeastern portion of the Subbasin (cross-section A-A' in **Figure 3**) limit groundwater flow within and out of the basin. The Coyote Creek Fault is assumed to be a 'no flow' boundary condition in the USGS Groundwater Model and as such serves to contain groundwater within the basin and direct flow to the southeast towards the Borrego Sink. The current-day topography combined with the geologic structure creates a 'closed' groundwater condition where ongoing evaporation of water will lead to the long-term accumulation of minerals (often referred to as 'salts') in soil and groundwater.
- While the lower aquifer is quite deep and contains a significant volume of groundwater, the sediments have less storage capacity than the upper and middle aquifers as quantified in the USGS Model by lower specific storage and specific yield. The lower aquifer is also expected to have poor water quality with depth.
- Waters that flow into the Subbasin from the adjacent watersheds will have varying chemistry depending on the geologic and hydrologic conditions encountered in the watersheds. For example, water that flows in Borrego Palm Creek from nearby crystalline rock of the San Ysidro Mountains (see **Figure 1**) will be different than the waters of San Felipe Creek that drain from an alluvial desert valley and more likely to accumulate dissolved minerals.

Please refer to the GSP for additional details.

FIGURE 3

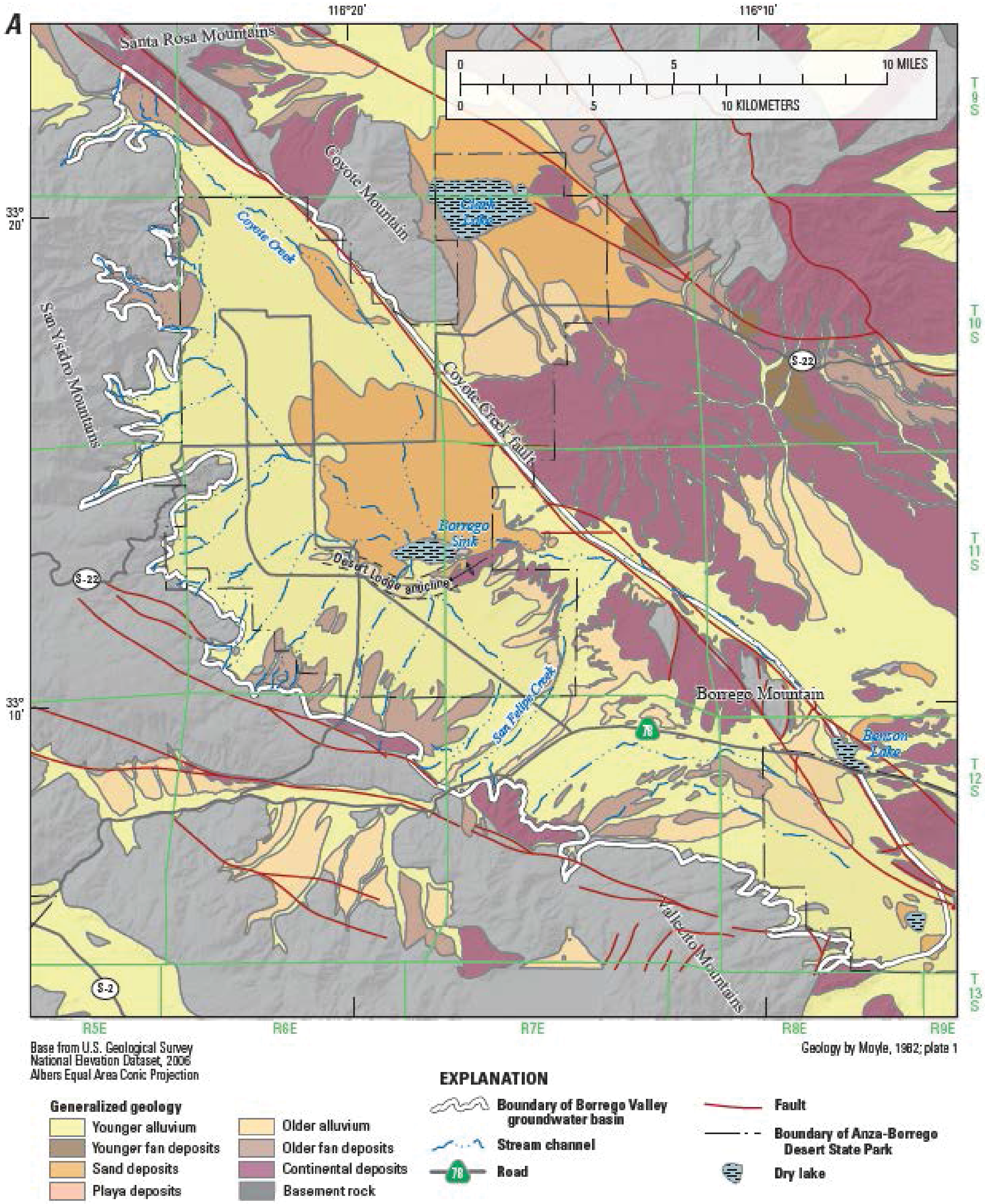


Figure 7. Maps showing Borrego Valley, California, showing *A*, geology; *B*, hydrogeology; and *C*, generalized hydrogeologic cross sections A-A' and B-B'. (Lines of section are shown in figure 7B.)

FIGURE 3, continued

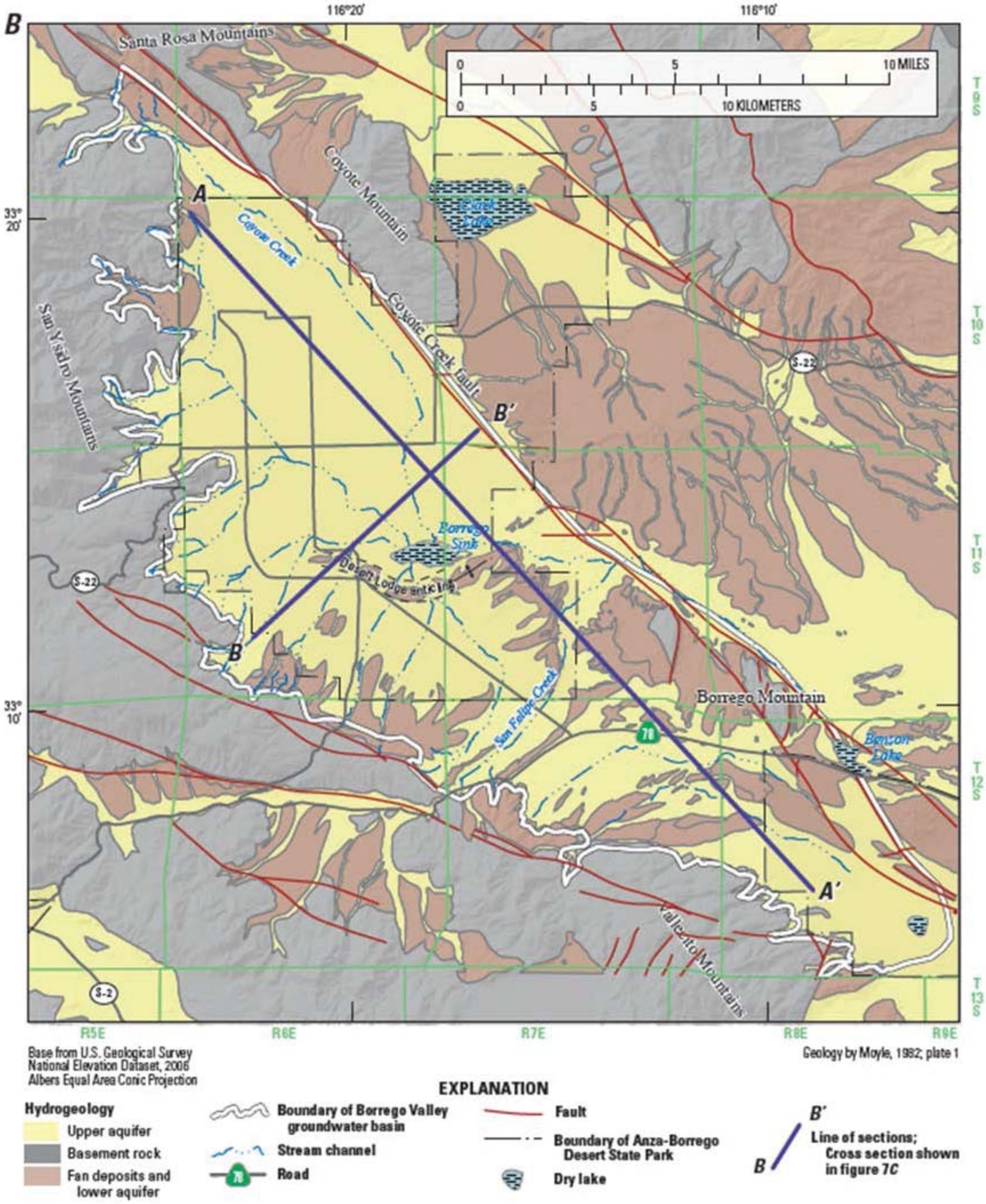
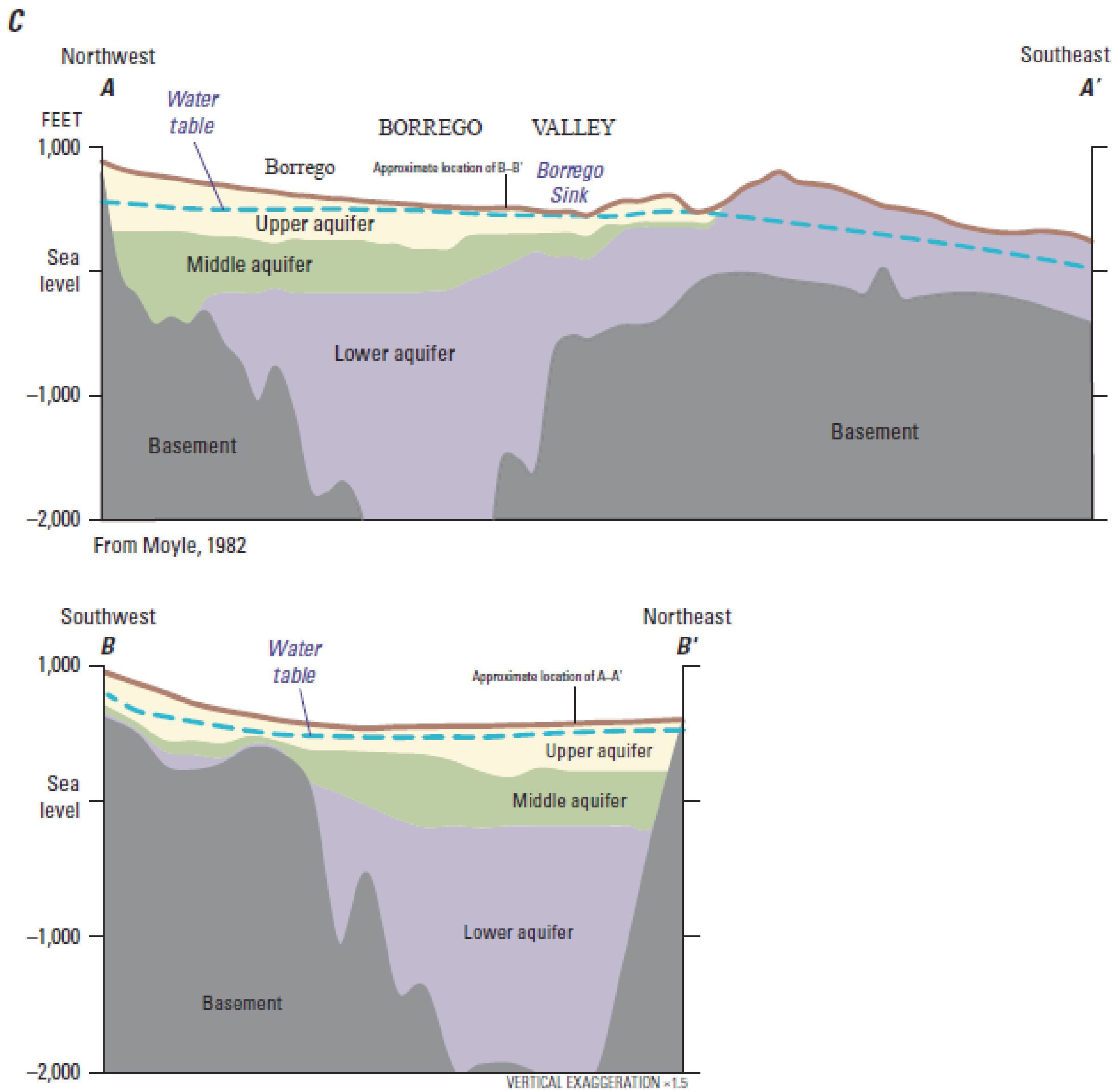


Figure 7. —Continued

FIGURE 3, continued



2.0 WELLS AND DATA USED IN THIS ANALYSIS

A total of 23 wells were included in this water quality analysis. Of these eight are active BWD supply wells and a ninth is used for emergency supply. The data for the wells were compiled and tabulated by Dudek staff as part of the GSP preparation process.

It is important to note that the wells were typically completed with long screened sections and can be open to flow from the upper, middle, and/or lower aquifers depending on the well construction, current groundwater levels, and well hydraulics. As a result, the data were not segregated by aquifer or depth.

Table 1A lists the active BWD wells and indicates the time periods when general minerals data were obtained. The wells have been segregated into three management areas (North, Central, and South) as established in prior work by Dudek.

TABLE 1A: BWD Water Supply Wells

Plot ID	Area	Well Name	GSA GWM Well	Year Inst.	gpm	Static Water Level (ft)	Draw Down (ft)	gpm/ft ***	Plant Eff.****	Well Depth (ft)	Sampling Period	
											start	end
4	North	**ID4-4***	Yes	1979**	365	205.4	63.5	6	71	802	1954**	2017
5		**ID4-11**	Yes	1995	620	223.2	5.8	107	73	770	1995	2017
2		**ID4-18***	Yes	1982	130	311.2	7.6	17	50	570	1984	2017
14	Central	**ID1-10***	Yes	1972	317	213.9	11.5	28	54	392	1972	2017
9		**ID1-12**	No	1984	890	145.5	10.4	86	72	580	1988	2018
12		**ID1-16**	Yes	1989	848	230.9	24.3	35	71	550	1993	2016
8		**ID5-5**	Yes	2000	542	182.1	16.1	34	62	700	2004	2016
13		**Wilcox**	Yes	1981	205	305.2	5.8	35	NA	502	2000	2017
15	South	**ID1-8**	Yes	1972	448	71.2	47.7	9	51	830	1972	2018

Notes: Data from 2018 Pump Check Results (in Dudek New Wellsite Feasibility Report, in process)
*, wells being considered for replacement (3)
**, ID4-4 was redrilled in 1979.
***, gpm/ft calculated from Pump Check data
****, Plant Efficiency from Pump Check, in percent. Values less than 60% are viewed to be of concern.

The 'plot ID' listed in **Tables 1A and 1B** supports the map-based location of the wells and roughly proceeds from north to south.

TABLE 1B

Plot ID (Figure 7)	Management Area	in GWM program?	Water Quality: 2Q 2018 (MCL as indicated) TDS (500/1000 mg/L)	F (2 mg/L)	NO3 (as N, 10 mg/L)	SO4 (250/500 mg/L)	As (10 ug/L)	Well Name		gpm	TD (msl)	Year Inst.	notes	anion/cation trend over time (see Piper Diagram)
3	North	.					<2	ID4-3	IA	no data			last tested 2007	Percent Sulfate Increased, may be stable; Calcium has been variable
4		yes	330	0.16	0.5	110	2.2	ID4-4	A*	365	-204	1979	(redrilled 1979)	Fairly stable (new well),
1		.					0	ID4-7/ Anza#4	IA	no data			last tested 1983	Percent Sulfate Increased (1973 to 1983)
5		yes	380	0.23	0.56	90	1.2J	ID4-11	A	620	-156	1995		Fairly stable
2		yes	**630**	0.87	0.54	**270**	<1.2	ID4-18	A*	130	-121	1982		Percent Sulfate Increasing
14	Central	yes	340	0.48	1.3	67	2.8	ID1-10	A*	317	-203	1972		Variable over time, no clear trend
9		yes	300	0.35	0.34	95	2.5	ID1-12	A	890	-48	1984		Fairly stable
12		yes	300	0.44	1	58	2.0	ID1-16	A	848	40	1989		Fairly stable
7A		.					<3	ID4-1	IA	no data			last tested 1980	Becoming more Calcium dominant (last gen min data 1980)
10		.					2.3	ID4-2	IA	no data			last tested 2010	Large change in 2010 (dec Sodium), no recent data to assess trend
7		.					2	ID4-5	IA	no data			last tested 1994	Limited data to assess trend
11		.					<2	ID4-10	IA	69?	200	1989	last tested 2012	Fairly stable
8		yes	330	0.8	0.39	100	2.1	ID5-5	A	542	-124	2000		Percent Sulfate Increased (2001 to 2013), may now be stable
6		.					6.4	Cocopah	A	1166	-393	2005	last tested 2013	Limited data to assess trend
13		yes	230	0.64	1.00	19	3.8	Wilcox	(A)	205	198	1981		Increasing bicarbonate, decreasing Calcium
20	South	yes	**1600**	0.18	0.76	**700**	<1.2	ID1-1	IA	200	-75	1972		Major changes 1972 to 2017: Increasing sulfate and Calcium; dec bicarbonate
21		yes	320	0.49	2.9	36	5.5	ID1-2	IA	200	-157	1972		Major changes 1972 to 2017: Increasing bicarbonate
15		yes	490	0.62	1.6	86	4	ID1-8	A	448	-335	1972		Increasing Sulfate and Chloride, Increasing Calcium
22		yes	**830**	0.56	0.5	**350**	**15**	Jack Crosby	(A)	10	194	2004		Limited data to assess trend
-		yes	640	0.37	**20**	100	2.5	WWTP	mw	mw	404	2009		Gen min data failed QA/ not assessed
16		yes	nm	nm	nm	nm	**15**	RH-3 (2017 data)	A	230	-323	2014		Limited data to assess trend
17		yes	400	1	0.49	110	6.3	RH-4	A	260	-147	2014		Limited data to assess trend
18		yes	480	1.3	3.6	100	**15**	RH-5	A	350	-169	2015		Increasing Bicarbonate
19		yes	330	1.2	3.3	31	**13**	RH-6	A	350	-312	2015		Limited data to assess trend
-		yes	450	0.51	1.2	76	2.8	MW-3	mw	mw	197	2005		Limited data to assess trend

xx exceeds the MCL
note: Secondary MCLs apply to TDS and Sulfate
Reccomended and maximum values
are listed for TDS and Sulfate

A* active BWD Production Well, * indicates wells cuurently slate for replacement due to condition
A active non-BWD Production Well
IA Inactive BWD Well
mw Monitoring Well

Figure 4 shows the well locations and names used in this Report. Review of **Figure 4** shows that the well locations are spatially biased along the western portion of the valley and the Subbasin. This is because the BWD wells are located in populated areas within their historical service areas (or Improvement Districts [ID] as indicated by the well names).

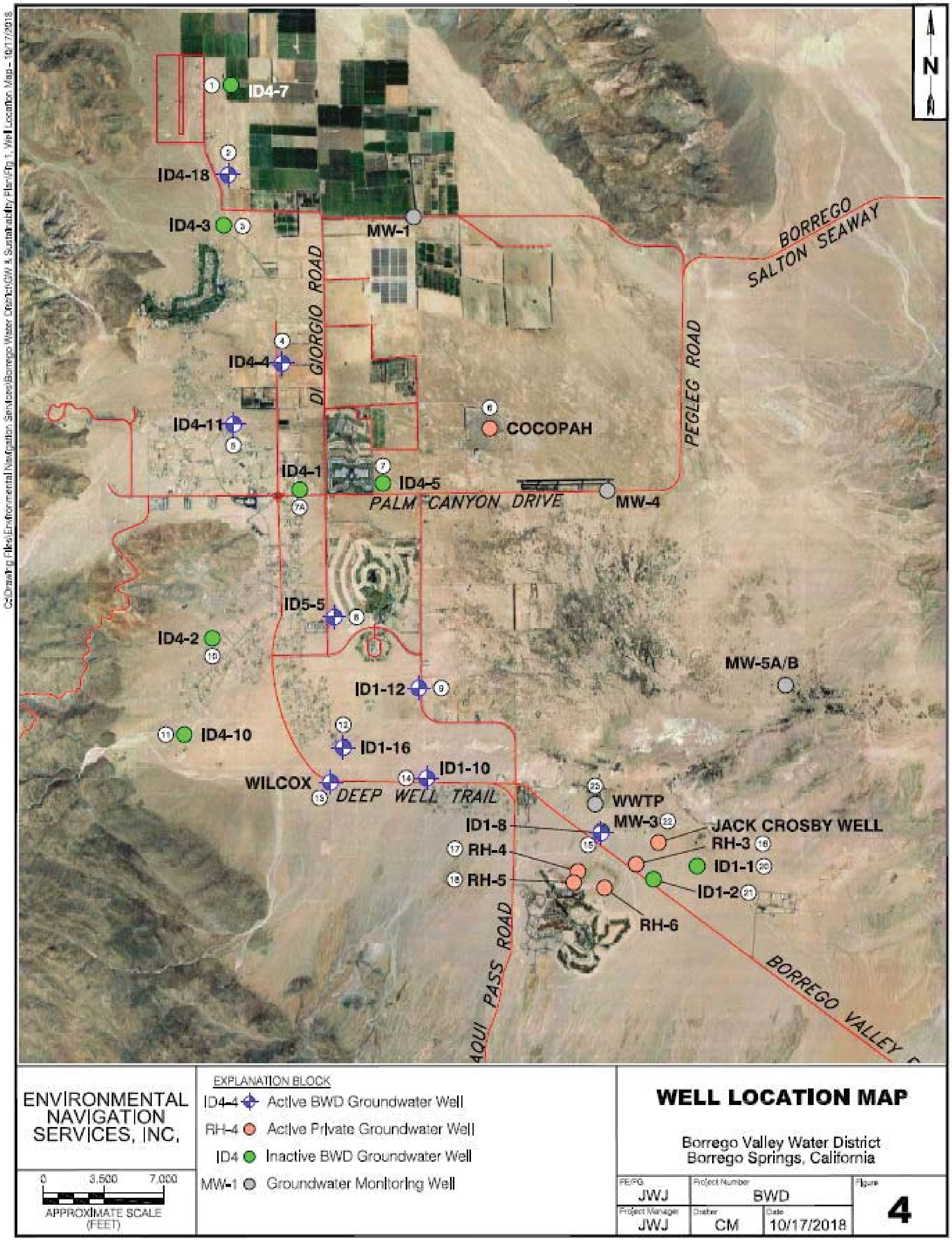
The analytical data used in the Report were located and compiled by Dudek staff from multiple sources as part of the GSP preparation process. The data base used here is from July 2018- the GSP data base is updated and revised on an ongoing basis. This Report focuses on:

- Chemicals of Concern (COCs) that include arsenic, TDS, nitrate, sulfate, and fluoride (As, TDS, NO_3, SO_4, and F).
- General Minerals: comprised of four cations- calcium (Ca^{+2}), sodium (Na^{+}), magnesium (Mg^{+2}), and potassium (K^{+}); and four anions- sulfate (SO_4^{-2} [also a COC]), chloride (Cl^{-}), carbonate (CO_3^{-2}) and bicarbonate (HCO_3^{-}).
- Hardness and pH.

The overall intent of this Report is to assess the use of multiple water quality parameters to examine how the primary COCs at BWD wells vary over time and to examine the likelihood that drinking water quality criteria will be exceeded. Of primary concern are arsenic and nitrate. Sulfate is also of concern.

Other COCs not examined in this Report include pesticides, herbicides, naturally-occurring radionuclides, and unregulated contaminants for which monitoring is required. Per State Law the Borrego Water District tests their water supply wells in accordance with California Code of Regulations Title 22 for a wide variety of potential contaminants because they operate a publicly-regulated water system. For additional information refer to their Consumer Confidence Report (CCR, available at http://www.bvgsp.org/sgma-blank.html).

FIGURE 4



ID4-7
ID4-18
ID4-3
MW-1
BORREGO SALTON SEAWAY
DI GIORGIO ROAD
ID4-4
ID4-11
COCOPAH
PEGLEG ROAD
ID4-1
ID4-5
PALM CANYON DRIVE
MW-4
ID5-5
ID4-2
MW-5A/B
ID1-12
ID4-10
ID1-16
ID1-10
WILCOX
DEEP WELL TRAIL
WWTP
MW-3
JACK CROSBY WELL
ID1-8
RH-3
RH-4
ID1-1
RH-5
ID1-2
RH-6
YAQUI PASS ROAD
BORREGO VALLEY
N
ENVIRONMENTAL NAVIGATION SERVICES, INC.
0 3,500 7,000
APPROXIMATE SCALE (FEET)
EXPLANATION BLOCK
ID4-4 Active BWD Groundwater Well
RH-4 Active Private Groundwater Well
ID4 Inactive BWD Groundwater Well
MW-1 Groundwater Monitoring Well
WELL LOCATION MAP
Borrego Valley Water District
Borrego Springs, California
PE/PG JWJ
Project Number BWD
Figure 4
Project Manager JWJ
Drafter CM
Date 10/17/2018

3.0 SUBBASIN-WIDE WATER QUALITY: GENERAL MINERALS, ARSENIC, AND NITRATE

The term “general minerals” is a descriptor that includes the eight anions and cations that typically comprise most of the minerals, by mass, dissolved in groundwater. Anions are negatively charged and cations are positively charged. The eight dominant ions include four cations- calcium (Ca^{+2}), sodium (Na^{+}), magnesium (Mg^{+2}), and potassium (K^{+}); and four anions- sulfate ($SO4^{-2}$), chloride (Cl^{-}), carbonate ($CO3^{-2}$) and bicarbonate ($HCO3^{-}$). Of these, sulfate is a COC. TDS is also a COC and represents the sum all of the anions and cations in solution.

Table 2. Common Cations and Anions Analyzed in the Subbasin

Common Cations	Common Anions
calcium (Ca^{+2})	sulfate (SO_4^{-2})
sodium (Na^{+})	chloride (Cl^{-})
magnesium (Mg^{+2})	carbonate (CO_3^{-2})
potassium (K^{+})	bicarbonate (HCO_3^{-})

The dominant anions and cations can be used to examine how the chemistry of groundwater varies in time at a well, or spatially among wells. Because they occur as a result of rock and mineral dissolution, they can also be diagnostic of minerals such as sulfates and carbonates that occur in the subsurface, or that occur in water being recharged to the aquifer system.

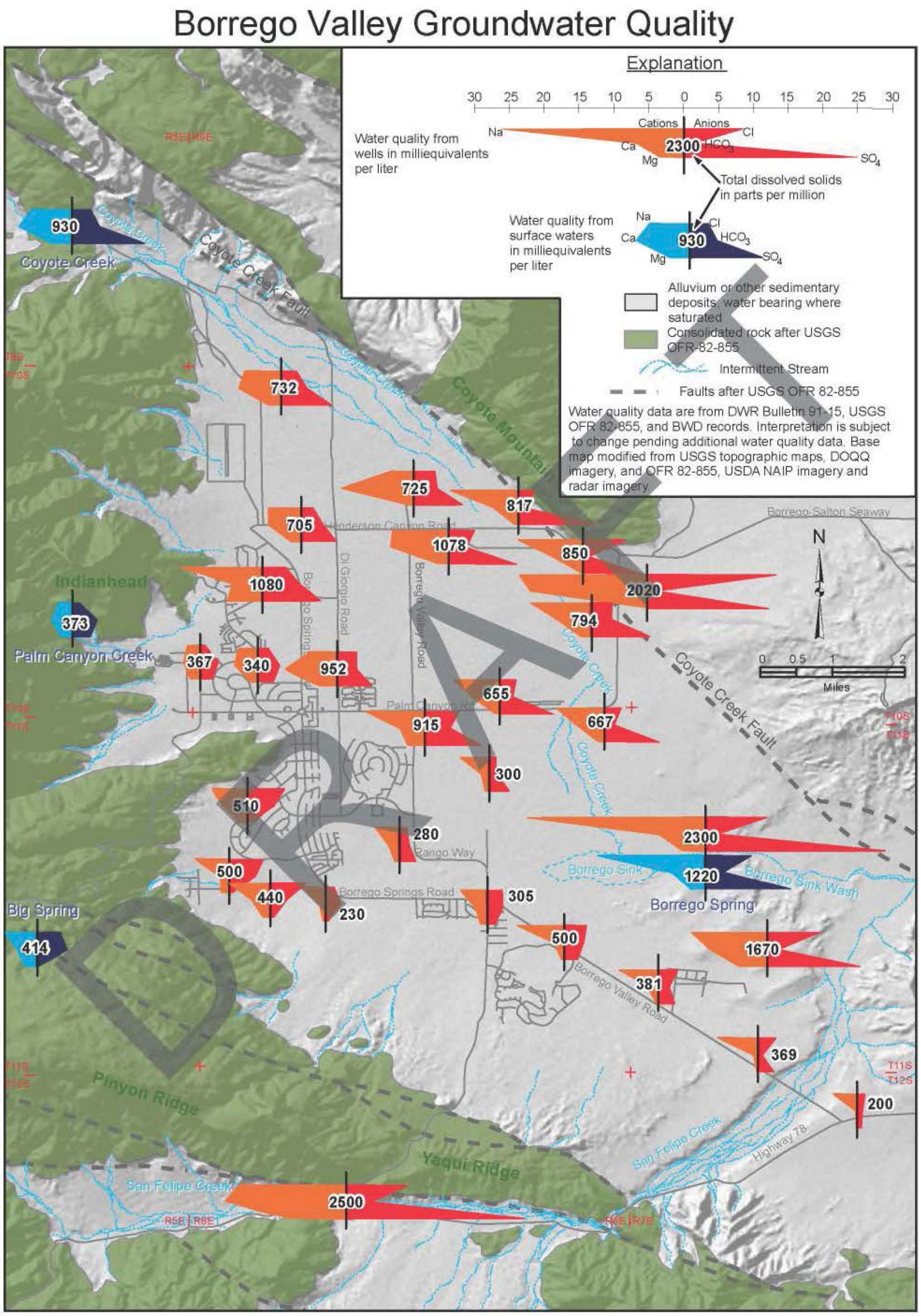
Graphical methods used to depict multiple anions and cations include Stiff Diagrams and Trilinear or Piper Diagrams.[10] Both are used in this Report and will be explained in more detail in Sections 3.1 and 3.2, respectively.

3.1 Spatial Overview (DWR, 2014; Stiff Diagrams)

Stiff diagrams graphically depict the relative concentrations of three dominant anions (Cl, HCO3, and SO4) together with three dominant cations (Na, Ca, and Mg) determined from water samples.[11] A 2014 groundwater quality study was conducted by the California Department of Water Resources (DWR)[12] based on the compilation of DWR, BWD, and USGS water quality data generally obtained between 1950 and 2014. A map depicting Stiff Diagrams of water quality is depicted in **Figure 5**.

[10] An overview summary is provided by: Hem, J.D., 1989, Study and interpretation of the chemical characteristics of natural water: U.S.
Geological Survey Water-Supply Paper 2254, 3rd edition, Washington D.C., 263 p.
[11] Stiff, H.A., Jr., 1951, The interpretation of chemical water analysis by means of patterns: Journal of Petroleum Technology, v. 3, no. 10, p. 15-17.
[12] DWR, 2014. Powerpoint presentation by Dr. Tim Ross dated May 2014. A copy is included for reference in **Appendix A**.

FIGURE 5


Borrego Valley Groundwater Quality
Explanation
Water quality from wells in milliequivalents per liter
Cations
Anions
Na
Ca
Mg
Cl
HCO3
SO4
2300
Total dissolved solids in parts per million
Water quality from surface waters in milliequivalents per liter
930
Alluvium or other sedimentary deposits, water bearing where saturated
Consolidated rock after USGS OFR-82-855
Intermittent Stream
Faults after USGS OFR 82-855
Water quality data are from DWR Bulletin 91-15, USGS OFR 82-855, and BWD records. Interpretation is subject to change pending additional water quality data. Base map modified from USGS topographic maps, DOQQ imagery, and OFR 82-855, USDA NAIP imagery and radar imagery.
Coyote Creek
Coyote Creek Fault
Coyote Mountain
Indianhead
Palm Canyon Creek
Henderson Canyon Road
Di Giorgio Road
Borrego Valley Road
Palm Canyon Rd
Rango Way
Borrego Springs Road
Borrego Sink
Borrego Sink Wash
Borrego Springs
Big Spring
Pinyon Ridge
Yaqui Ridge
San Felipe Creek
Highway 78
Borrego-Salton Seaway
N
Miles
DRAFT

An explanation of how the analytes are depicted using Stiff Diagrams is also included in **Figure 5**. The 'legs' and overall size of the diagrams increase as the analytes increase in concentration and allow visual comparison of each of the sample results. Also included in the diagrams is the TDS in milligrams per liter. For reference the TDS of drinking water should be no more than 1,000 mg/L and ideally less than 500 mg/L (the recommended and maximum secondary MCLs, respectively).

DWR noted based on comparison of surface water and groundwater chemistry that "*The high proportion of Sulfate in the surface water of Coyote Creek appears to dominate the character of groundwater in the northern and eastern parts of the basin. The more Bicarbonate waters of Borrego Palm Canyon and Big Spring influence the groundwater along the western and southern parts of the basin.*" For reference, the surface water watersheds are shown in **Figure 1**.

Additional observations that can be made from the Stiff Diagrams include:

- Surface water inflows that enter the along the edges of the valley are the primary source of recharge. The highest quality groundwater (TDS < 500 mg/L) generally occurs near recharge areas.
- Groundwater quality tends to increase in TDS towards the Borrego Sink with distance from the recharge areas. Ongoing evaporation and accumulation of minerals is occurring within the Subbasin. The Subbasin is effectively a closed basin and has been a closed basin during much of the time that alluvial sediments have been deposited from current watersheds. (Please refer to the GSP for a detailed description of the Subbasin geology and sedimentology.)
- Elevated concentrations of sulfate in surface waters are of concern from a water quality standpoint. Groundwater within the San Felipe Creek watershed that potentially recharges the South Management Area contains relatively high concentrations of sulfate, calcium and sodium.
- The Stiff Diagrams highlight the dominance of sulfate in groundwater (lower right portion of the diagrams). Sodium and chloride (upper right and upper left 'legs') also occur at significant concentrations in many samples.

The DWR presentation also reviewed TDS trends with time and depth at selected wells. No consistent trends were identified. The data were not evaluated in terms of the upper, middle, or lower aquifer.

DWR also assessed nitrate. Review of their results is included in **Section 3.5**.

3.2 General Minerals: Spatial Variability Based on Piper Diagrams

The eight dominant anions and cations can also be analyzed using Piper trilinear diagrams (Piper, 1944).[13] In brief, the Piper plot is a visualization technique for groundwater chemistry data. It is based on a combination of ternary diagrams for the major anions and cations that are then projected onto a central diamond. The concentration data on (milligrams/liter) are converted to milliequivalent (meq/L), a measure of the number of electrochemically active ions in the solution.[14] The analytes are plotted as relative proportions in order to examine the relative percentages of each of the dissolved minerals, primarily to show clustering or patterns of samples. The diagrams also support interpretation of trends and potential mixing of waters that have different chemistry.

Figure 6A provides a brief explanation of the Piper diagram. The methodology is explained in more detail in **Appendix B**, together with the Piper trilinear diagrams for all of the wells as noted in **Table 1B**. Ternary diagrams present a combination of three values that add up to 100 percent. The three values are 'picked off of' the sides of triangle by projection along a triangular grid. Please refer to **Appendix B** as needed for additional explanation.

Recent general minerals data, dating from 2004 to present, were used to represent the water chemistry at each of the wells. Review of the data supported the use of two data subsets. The North and Central Management Area wells have been combined and the South Management Area wells are presented as a second set. **Figure 6** depicts the data. Each of the wells are numbered per **Figure 4** and **Table 1** to simplify the data presentation. The numbering generally follows from north to south along the axis of the valley.

3.2.1 Data Quality Review: General Minerals

The data presented in the Piper diagrams underwent a data quality review based on the ion chemistry. Groundwater under natural conditions should be at or near electrochemical equilibrium. Here the sum of the negatively charged anions (in meq/L) was checked versus the sum of the positively charged cations. The sums should be similar (within ~5%) for a solution that is in equilibrium. Not all of the data were used because in some cases not all of the eight general minerals data were analyzed and in other cases the anion/cation balance test failed. As explained above, the anion/cation balance test may fail as a result of less common anions or cations being present within the water quality sample that were not analyzed. Charge imbalance may also indicate laboratory error.

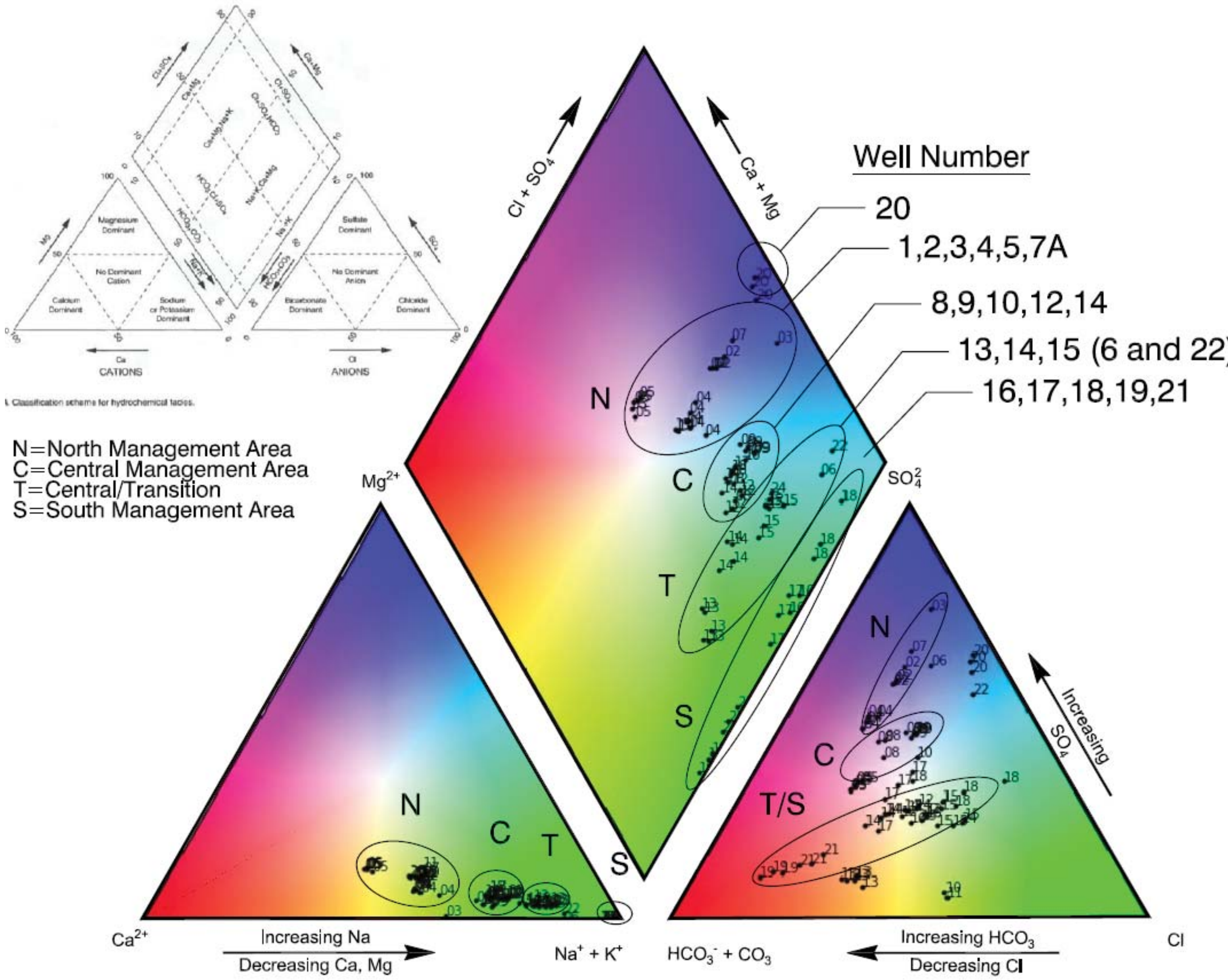
[13] Piper, A.M. 1944. A graphic procedure in the geochemical interpretation of water-analyses. Transactions-American Geophysical Union 25, no. 6: 914–923

[14] The number of ions in a solution is expressed in terms of moles, a unit widely used in chemistry as a convenient way to express amounts of reactants and products of chemical reactions. An equivalent is the number of moles of an ion in a solution, multiplied by the valence of that ion. For example, if 1 mole of NaCl and 1 mole of $CaCl_2$ are dissolved in a solution, there is 1 equivalent of Na, 2 equivalents of Ca, and 3 equivalents of Cl in that solution. The calculation is based on: mEq/L = (mg/L × valence) ÷ molecular weight.

The eight anions and cations generally comprise the bulk of the minerals that comprise TDS. Sodium and calcium are the dominant cations; bicarbonate, sulfate, and chloride are the dominant anions. The long-term average concentrations, in mg/L, for the nine BWD wells were TDS (378), calcium (39), sodium (82), magnesium (5.4), and potassium (5), sulfate (112), chloride (56), carbonate (0.6) and bicarbonate (124). Nitrate averaged 1.8 mg/L.

A calculation of TDS was made by summing the concentrations of the eight anions and cations and comparing it to the TDS for all samples that met a 5% or less charge imbalance criteria. On average the sum was less than the TDS by 40 mg/L, where the mass of cations exceeded the mass of anions. Other anionic COCs not included in the calculation include fluoride and nitrate, but when these were added into the calculations the mass of anions remained lower than the mass of cations. While the mass balances remained within tolerance, the results suggest that additional anions occur in groundwater that have not been tested. Phosphates are one type of anion that may occur but have not been included in the analytical program.

FIGURE 6: Piper Diagram, recent data for all wells (2004 to 2018)



Notes:

1. Numbers correspond to IDs shown in Figure 4. These generally increase from north to south.

2. The wells by management area include:

North Management Area: Wells # 1 to 5, #7, and #11

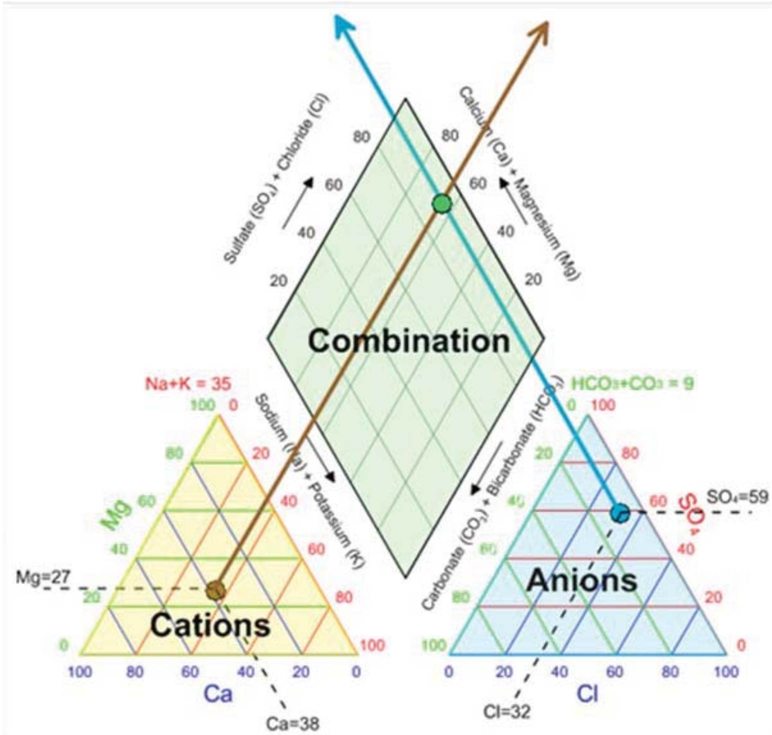
Central Management Area: Wells #8, #9, #10, and 12

"Transitional": Wells #6, #13, #15, #16, #22

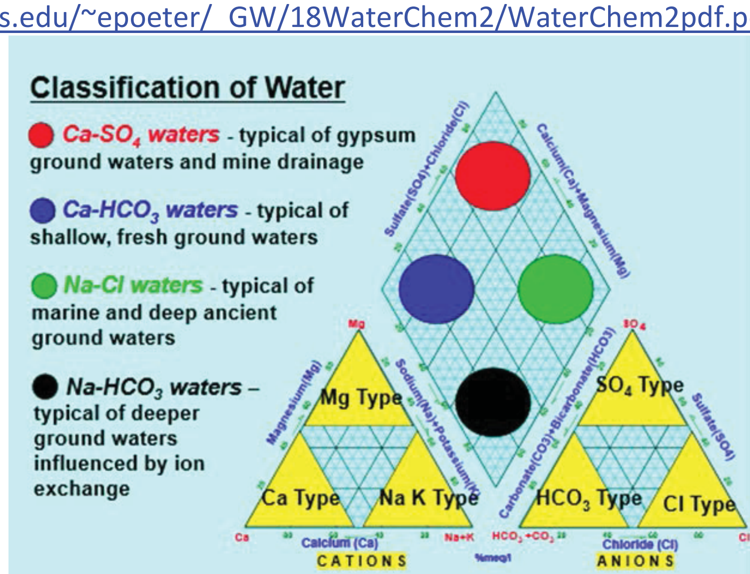
South Management Area: Wells #17 to 21, #23

FIGURE 6A

The Piper diagram is used to plot the 8 general minerals based on two ternary diagrams (triangles, at the base) that are projected onto a central diamond area. From (www.goldensoftware.com)



Where the subregions generally depict the chemical characteristics of the water (from http://inside.mines.edu/~epoeter/_GW/18WaterChem2/WaterChem2pdf.pdf)



Here colors are used to show subareas following a methodology presented by Peeters, 2014. (A Background Color Scheme for Piper Plots to Spatially Visualize Hydrochemical Patterns by Luk Peeters, Vol. 52, No. 1–Groundwater–January-February 2014). Also see **Appendix B**.

No distinction was made regarding well completion by aquifer because of a lack of water quality data as a function of depth. However, while the wells include a range of ell completions, the data do not indicate that any differentiation can be made among wells based on recent data (2004 to present). Review of the Piper Diagrams indicates that a systematic variation of water quality can be observed from north to south, and that the water quality in the South Management Area is sufficiently different to support segregation of the data into two data sets. Inorganic water quality depicted in the central Piper diagrams (**Figure 7**) indicates the data generally group by management area (MA): North MA (Wells # 1 to 7, and 11), Central MA (Wells #8, #9, #10, and 12), "Transitional" between the Central and South MAs (#13, #15, #16, #22), and South MA (#17 to 21, #23). Data from sets of wells align on the Piper diagram (**Figure 6**) indicative of waters that are mixing. Some general observations follow:

North and Central Management Areas

- A subset of the wells in the northern part of the basin (#1, #2, #3, and #4) occur along a line of anion data where high sulfate occurs.
- The North and Central Management Areas subdivide into two groups within the Piper diagram. With distance towards the south a general trend occurs where chloride decreases, bicarbonate increases, and sulfate decreases. Two mixing lines may occur where the waters go from sulfate dominant to a mixed condition (no dominant anion).

South Management Area

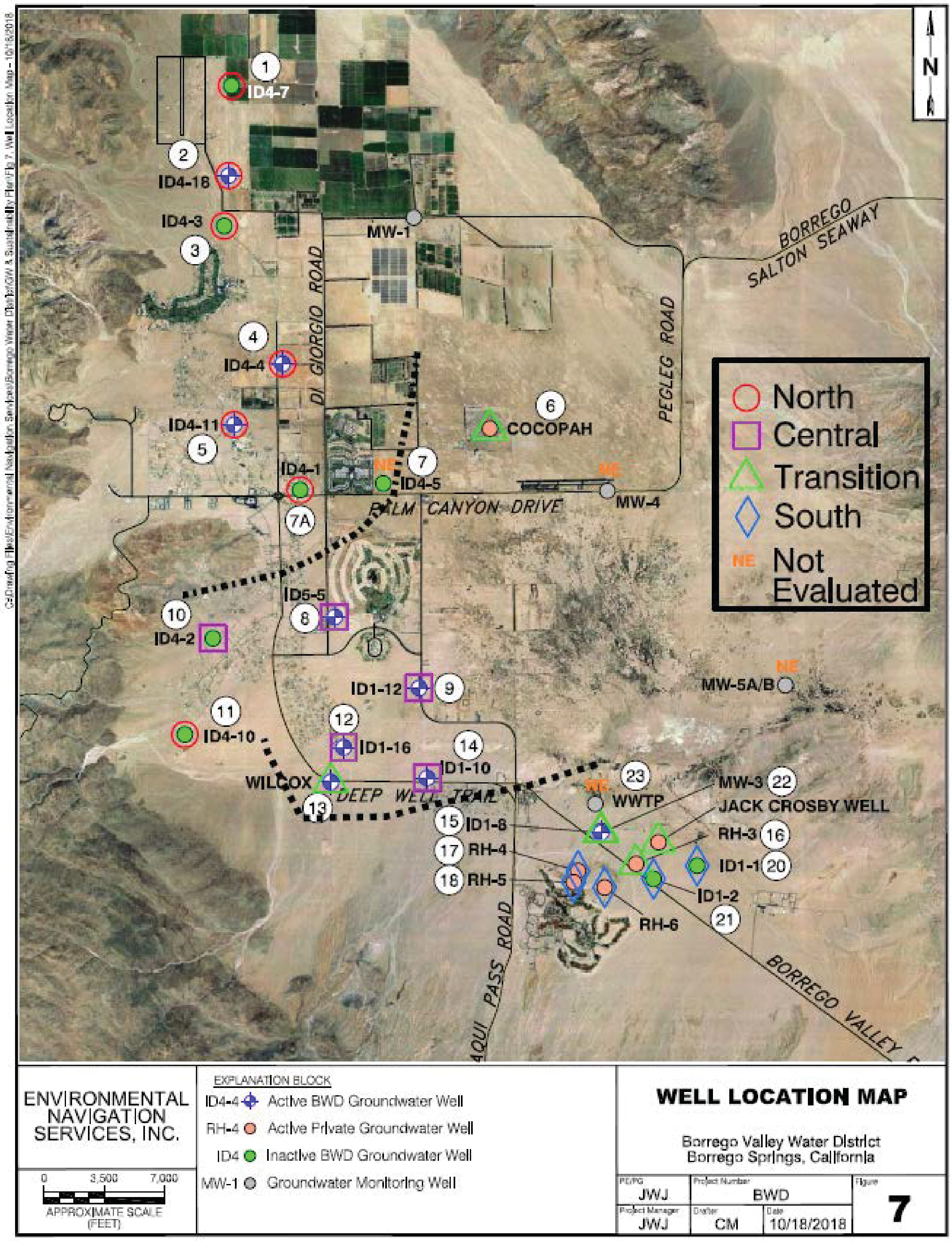
- A transitional zone occurs roughly coincident with the location of the Desert Lodge anticline (as depicted in **Figure 3**). The anticline is regarded as a structure that influences groundwater flow (refer to the GSP for further details).
- Mixing lines are observed for both cations and anions. For anions: as chloride decreases, bicarbonate increases, and sulfate decreases. For cations: as calcium decreases, sodium and magnesium increase.
- As also noted by the Stiff diagrams, the North Management Area has high sulfate as indicated by points that occur in the upper part of the cation ternary diagram. In contrast the South Management Area wells either have no dominant anion or become bicarbonate dominant (the lower left portion of the ternary diagram for anions).

Overall the Piper diagrams support that the inorganic water chemistry systematically varies across the Subbasin. The primary observations are summarized in **Figure 7**:

- Water quality gradually changes from north to south within the North and Central Management Areas, consistent with pre-development groundwater flow patterns.
- For both areas the cation relationships (calcium, magnesium, and sodium) are similar and are generally sodium dominant. In both cases the water quality is characterized by decreasing calcium and increasing percentages of sodium and magnesium.
- The South Management Area anionic water chemistry is different than the North and Central Management Areas, likely due to the difference in the San Felipe Creek recharge water and potential differences in aquifer mineralogy.

FIGURE 7

Shows water chemistry classified into the three Management Areas North, Central, and South. Also notes Transition (between central and south)



3.3 General Minerals: Variations Over Time at Wells, Piper Trilinear Diagrams

Of central concern to BWD and all other users of groundwater within the Subbasin is water quality degradation over time due to ongoing overdraft, irrigation and septic-related return flows, and loss of higher quality water due to dewatering of the upper aquifer. Piper trilinear diagrams were constructed for each of the wells using available historical data (compiled in **Appendix B**). Two examples are included as **Figures 8** and **9** where one well has had significant changes in water quality over time versus another that has been relatively stable.

The Piper diagrams depict relative ratios of the anions and cations, not the total concentrations. Also included in the figures are graphs of the anions and cations that present the measured concentrations (in mg/L).

ID1-8 (South Management Area, Well#15 on **Figure 7**)
Water chemistry has significantly changed over time at ID1-8. This well is in the South Management Area as depicted as Well #15 on **Figure 7**. It has been sampled since 1972. **Figure 8** includes a Piper Diagram and charts depicting TDS, cations, and anion concentrations over time.

Observed is historically decreasing bicarbonate, increasing chloride, and increasing calcium. Recent data indicates that water quality may be stabilizing.

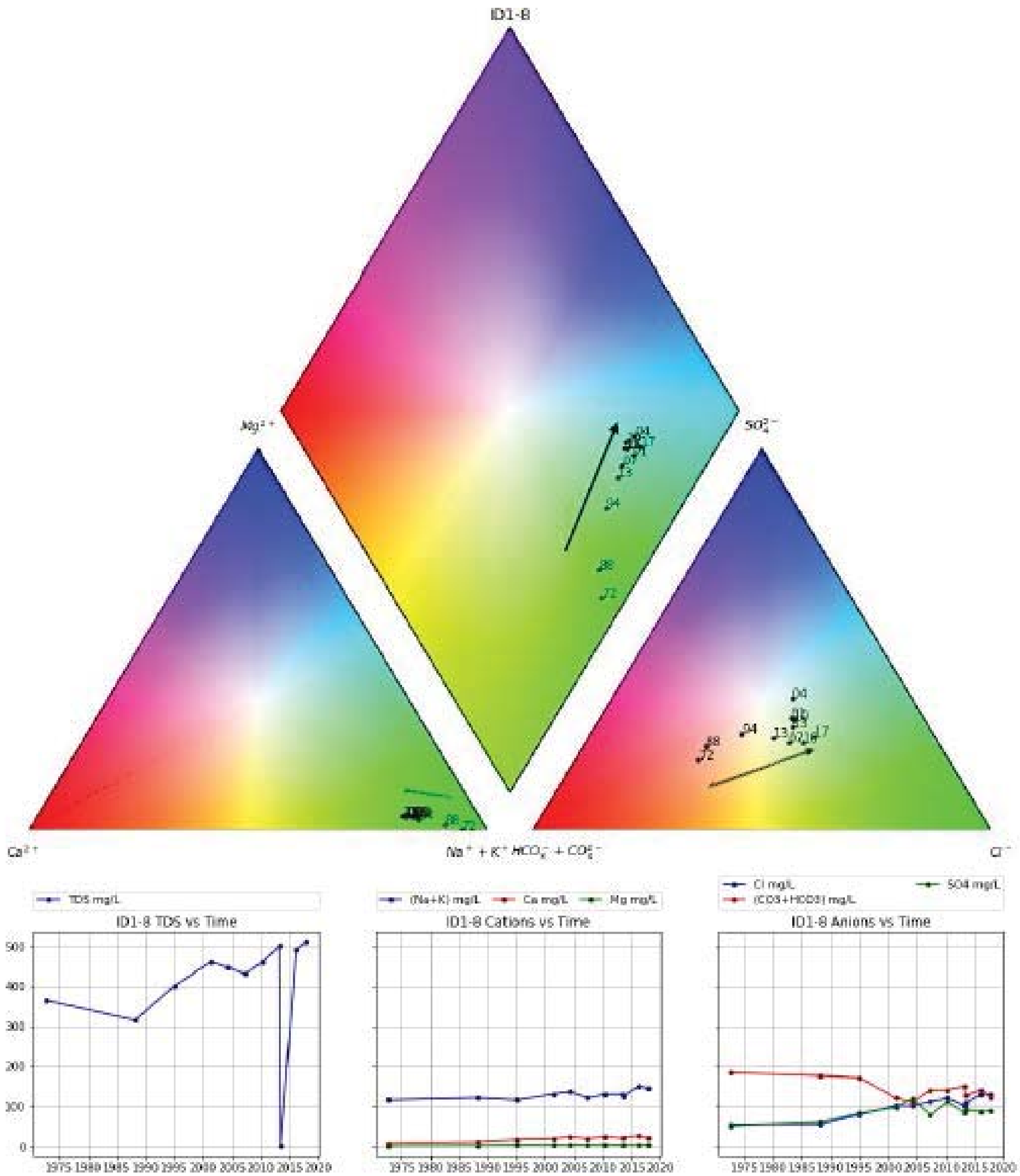
In terms of overall chemistry (see **Figure 6A**) the water in this well in now described as sodium chloride dominant, typical of marine and deep ancient groundwater.

ID4-18 (North Management Area, Well #2 on **Figure 7**)
This well is in the North Management Area as depicted as Well #2 on **Figure 7**. It also has been sampled since 1972. **Figure 9** includes a Piper Diagram and charts depicting TDS, cations, and anion concentrations over time.

There is much less overall change with time compared to ID1-8, but the sampling data do show sulfate is increasing. The change is subtle change but significant since concentrations are above the recommended secondary MCL of 250 mg/L, but do remain below the upper MCL of 500 mg/L. Sulfate is increasing as bicarbonate decreases over time. The points in the anion portion of the diagram (lower right triangle) occur along a line indicative of increasing sulfate.

In terms of anion chemistry (see Figure 6A) the water in this well in now described as sulfate dominant. Sulfate is a COC.

FIGURE 8: ID1-8 (see Figure 8A for explanation of the diagram and axes)

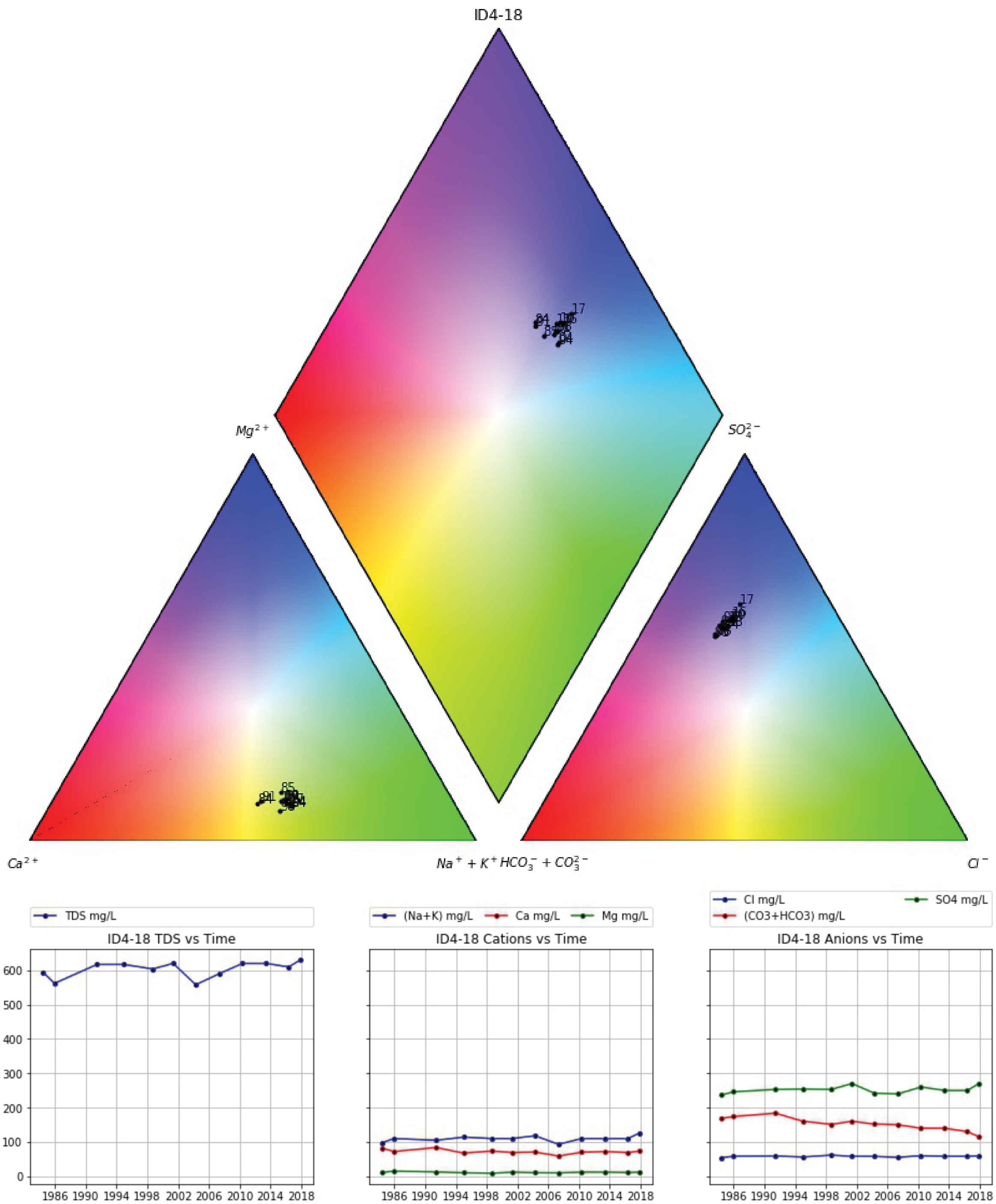


Notes:

1. The last two digits of the year the samples were taken are shown in the Piper diagram.

2. Chemistry has changed due to increases in sulfate, chloride, and sodium; and decreased bicarbonate. The change from 1970s to the 2000s is evident. TDS is also increasing.

FIGURE 9: ID4-18



Note:

1. The last two digits of the year the samples were taken are shown in the Piper diagram.

2. Water chemistry is fairly stable with a slow increase in sulfate and decrease in bicarbonate.

3.4 TDS with Depth

Well profiles based on TDS and temperature were presented by the DWR in a 2014 presentation (as referenced in footnote #11, a copy is included in **Appendix A**). **Figure 10** presents the profile data obtained from eleven wells that ranged in depth from 280 to 900 feet. For reference BWD water supply wells currently range in depth from 392 to 830 feet (Table 1).

Review of **Figure 10** supports the following:

- TDS varied by well, with linear increase with depth at each well. The exception is well ID4-3 where a step-wise increase in TDS was observed at a depth of approximately 350 feet.
- Groundwater temperature was relatively warm, ranging from approximately 80 to 90 ^{o}F. All wells exhibited increasing temperature with depth.

Geologic conditions and lithologies do change with depth, and it is generally expected that water quality change will decrease with depth. While quite important towards understanding the effect of overdraft on water quality, relatively few depth-specific groundwater chemistry data have been obtained in the Subbasin. The data presented in **Figure 10** are obtained by lowering measurement probes into the wells and are relatively inexpensive to collect provided there are no obstructions in the well. Additional discussion of well profiling methods is included in the report recommendations.

FIGURE 10

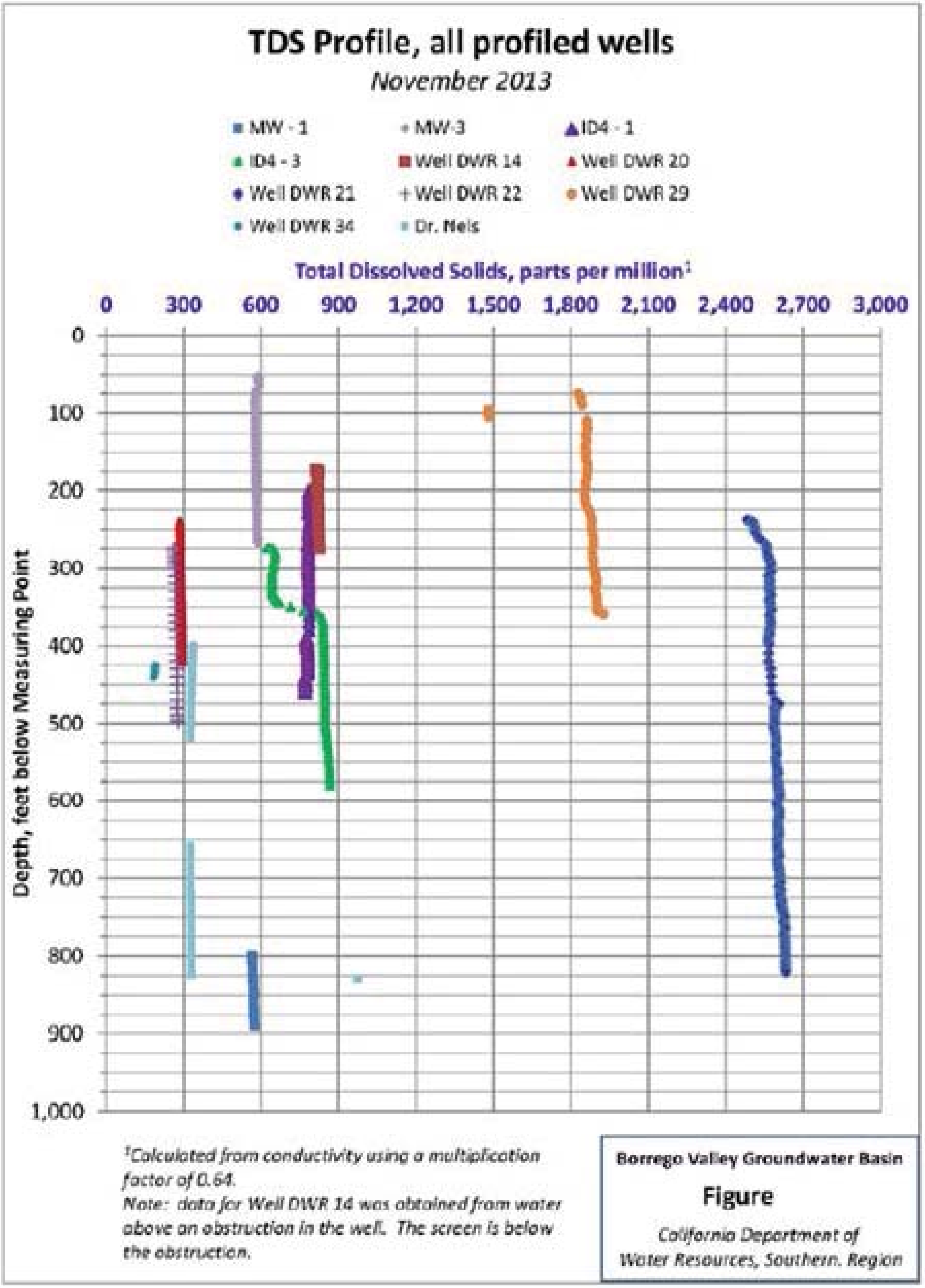
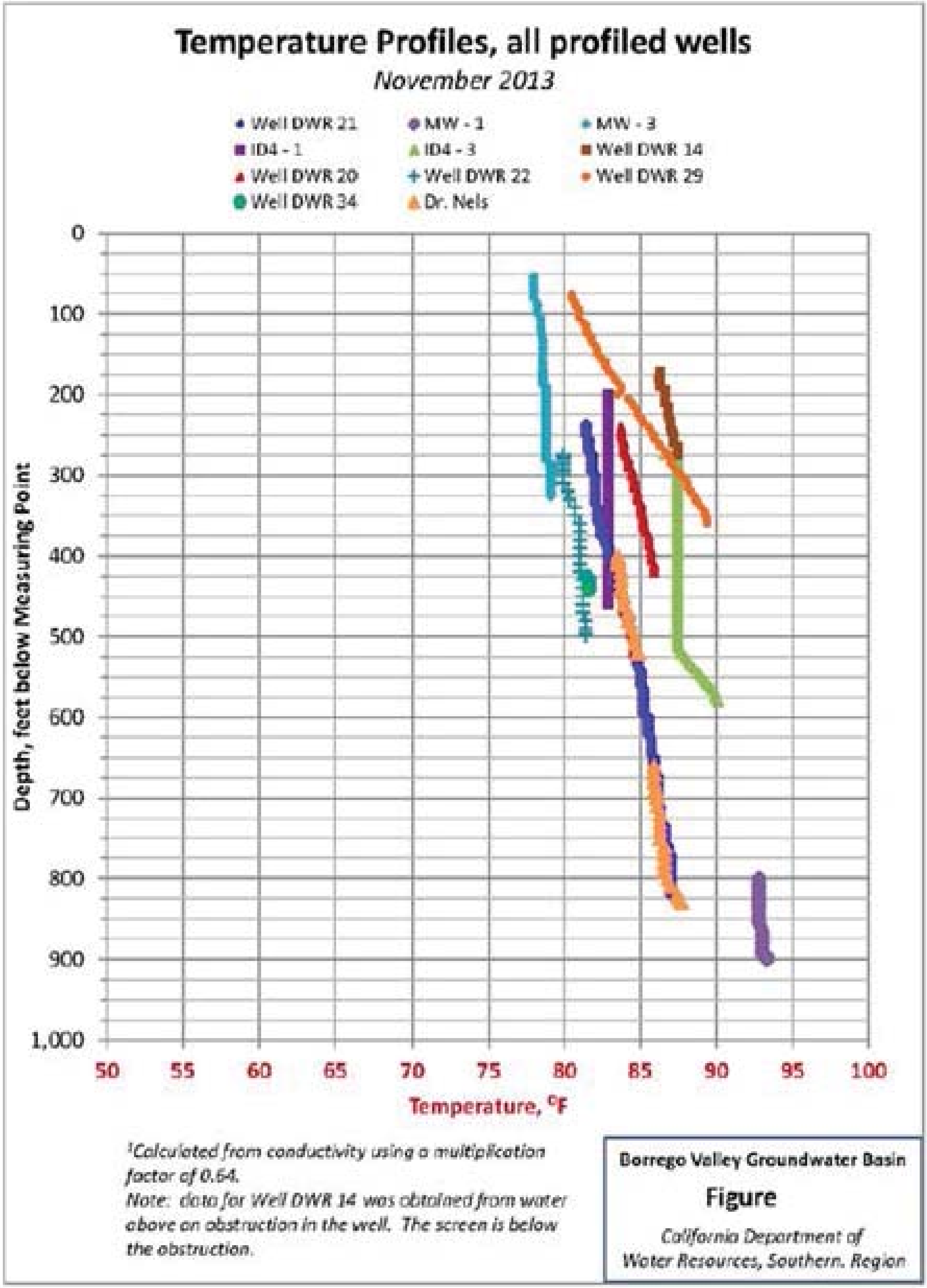

TDS Profile, all profiled wells
November 2013
MW - 1
MW-3
ID4 - 1
ID4 - 3
Well DWR 14
Well DWR 20
Well DWR 21
Well DWR 22
Well DWR 29
Well DWR 34
Dr. Nels
Total Dissolved Solids, parts per million¹
0
300
600
900
1,200
1,500
1,800
2,100
2,400
2,700
3,000
Depth, feet below Measuring Point
0
100
200
300
400
500
600
700
800
900
1,000
¹Calculated from conductivity using a multiplication factor of 0.64.
Note: data for Well DWR 14 was obtained from water above an obstruction in the well. The screen is below the obstruction.
Borrego Valley Groundwater Basin
Figure
California Department of Water Resources, Southern Region

FIGURE 10, continued



3.5 Nitrate

Nitrate (NO_3) is a groundwater contaminant that is commonly detected in drinking water supplies obtained from alluvial basins throughout the southwestern US (see, for example, USGS NAWQA[15], CA SWRCB GAMA[16], and others). Nitrate in groundwater has many natural sources, but nitrate concentrations in groundwater underlying agricultural and urban areas are commonly higher than in other areas. The primary sources of nitrate in the Subbasin include fertilizers associated with agriculture and turf grasses (golf courses), and septic systems.

The relationship between groundwater quality and overlying land uses was examined by DWR (DWR, 2014; in **Appendix A**). **Figure 11** shows "*the distribution of nitrate analyses for the Borrego Basin. Maximum content is shown per section and sections are colored according to the number of analyses in the section. Sections where the maximum contaminant level (MCL) are exceeded are shown in hatched patterns.*" The DWR analysis shows that nitrates occur above MCLs in multiple wells.

The USGS reviewed nitrate data and stated that "*TDS and nitrate concentrations were generally highest in the upper aquifer and in the northern part of the Borrego Valley where agricultural activities are primarily concentrated." (USGS Model Report, p.2) … "Water-quality samples from wells distributed throughout the valley show that NO_3-N concentrations ranged from less than 1 mg/L to almost 67 mg/L. NO_3-N concentrations were highest in the shallow aquifer and exceeded the CA-MCL of 10 mg/L in some samples from the shallow and middle aquifers in the northwestern part of the basin (fig. 26). NO_3-N concentrations in samples from the lower aquifer did not exceed 6.7 mg/L.*" (USGS Model Report p.64)

Further spatial analysis of the occurrence of nitrate relative to land use is not included in this report. Additional review of nitrate data is included in **Section 3.7**, and in the GSP.

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[15] Thiros, S.A., Paul, A.P., Bexfield, L.M., and Anning, D.W., 2014, The quality of our Nation's waters—Water quality in basin-fill aquifers of the southwestern United States: Arizona, California, Colorado, Nevada, New Mexico, and Utah, 1993–2009: U.S. Geological Survey Circular 1358, 113 p., http://dx.doi.org/10.3133/cir1358. National Ambient Water Quality Assessment (NAWQA)

[16] Groundwater Ambient Monitoring and Assessment Program (GAMA
See:)https://www.waterboards.ca.gov/gama/

3.5.1 Supporting Information Regarding Nitrate

Historical groundwater quality impairment for nitrates is noted in the GSP to predominantly occur in the upper aquifer of the North Management Area underlying the agricultural areas, and near areas with a high density of septic point sources. The primary source of nitrates is likely associated with either fertilizer applications.

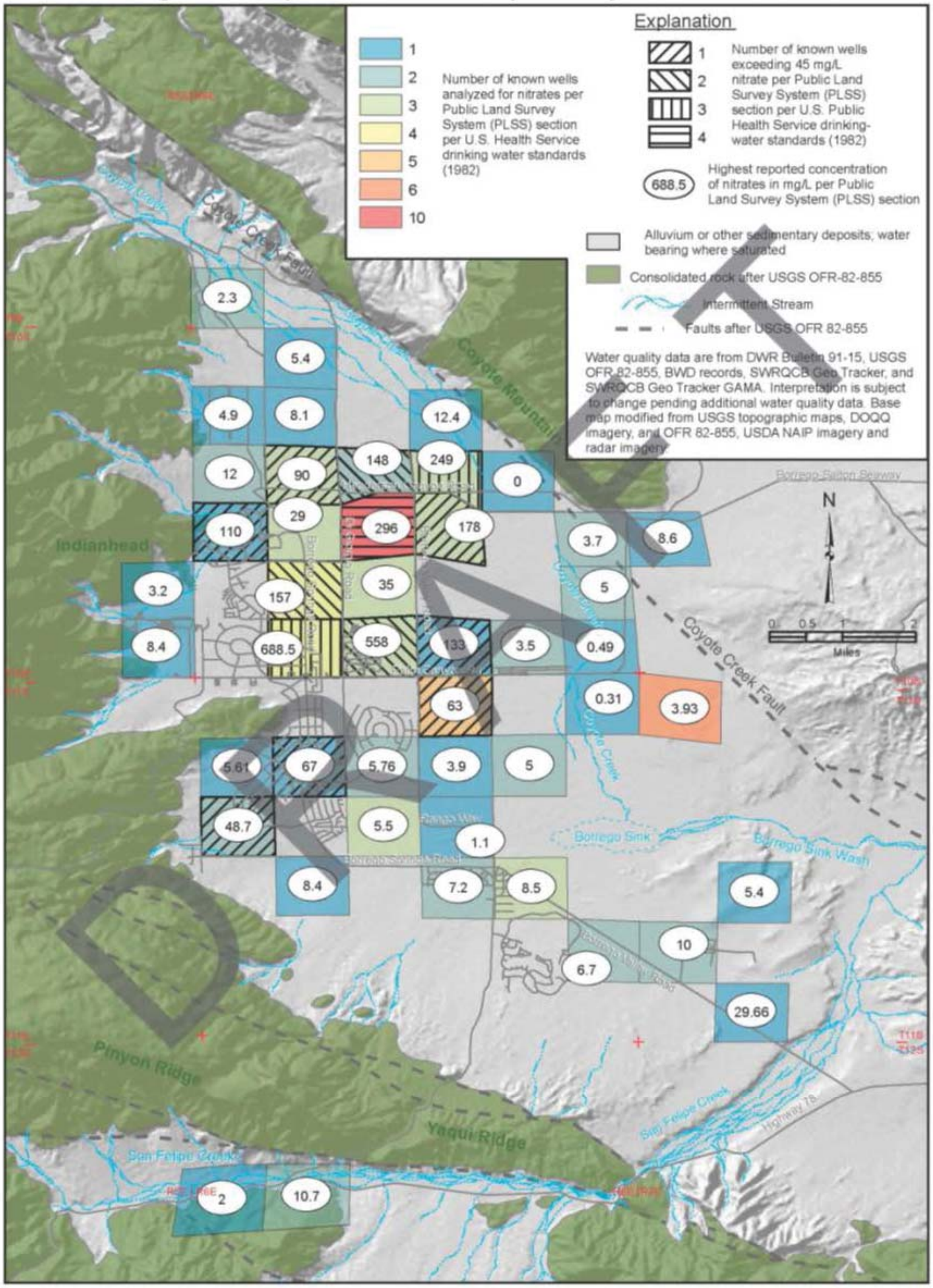
Information provided by Dudek in the GSP supports that nitrates have historically impacted multiple wells as follows. It is understood that the BWD Improvement District 4 (ID4) well 1 and 4, Borrego Springs Water Company Well No. 1 (located at the BWD office), the Roadrunner Mobile Home Park, and Santiago Estates wells were all taken out of potable service due to elevated nitrate. The latter two developments were connected to municipal wells operated by the BWD as an alternative source of supply. Well ID4-4 was re-drilled and screened deeper at the same location and successfully accessed good water quality not impacted by nitrates. The DiGiorgio wells 11, 14 and 15 located north of Henderson Road have historical detections of nitrate and TDS above drinking water standards. The existing groundwater network indicates elevated nitrate currently occurs at the Fortiner well No.1 in the North Management Area and at the BWD's WWTP monitoring well (see map, **Figure 4**).

Nitrate contamination enters the unconfined aquifer system via irrigation return flows and septic system discharge. An unconfined aquifer is directly open to the downward percolation of water. Thus, the uppermost portion of the aquifer is the most susceptible to nitrate impacts. However, as noted in **Table 1B**, nitrate impacts have been observed at low concentrations in all of the active BWD water supply wells.

There are two factors that can facilitate the downward migration of nitrates within the aquifer system- both caused by wells. The first is that ongoing pumping from deeper portions of the aquifer can actively draw shallow groundwater deeper into the aquifer system. The second is that inactive wells can act as conduits for groundwater flow and facilitate the drainage of water from the upper aquifer into deeper aquifers because of downward hydraulic gradients induced by ongoing pumping and overdraft (see Recommendations, Section 5.2, for additional discussion).

FIGURE 11

Borrego Valley Water Quality Analyses of Nitrates

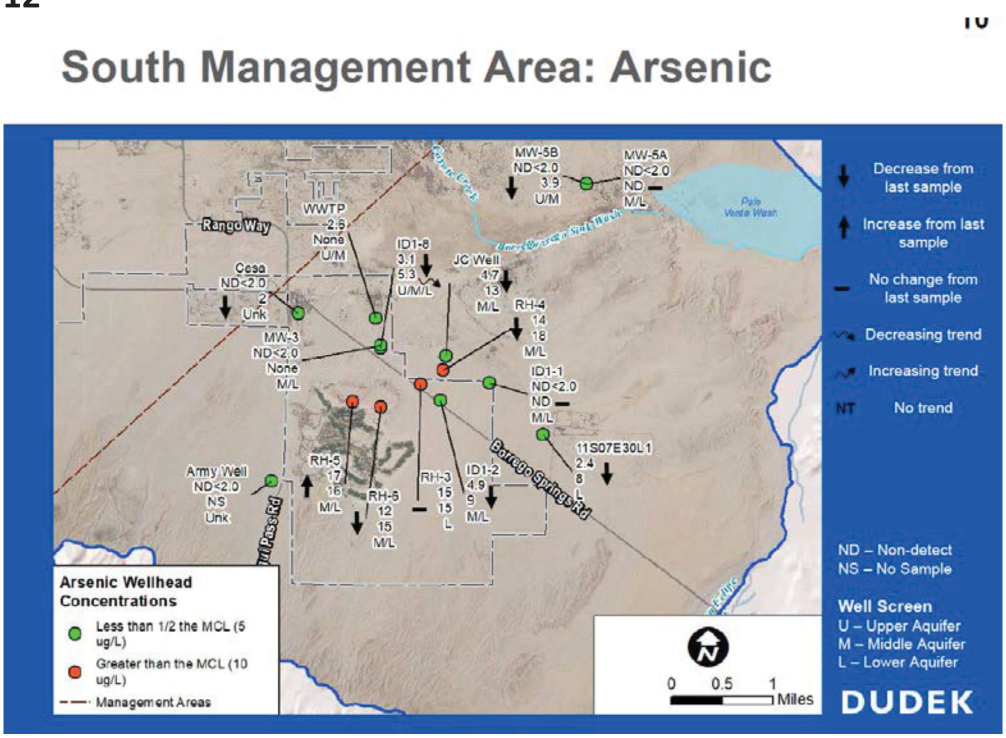


3.6 Arsenic

Arsenic is the primary drinking water COC identified throughout alluvial basins across the desert southwest (see, for example, previously cited USGS NWQA Report, 2014). The fate and transport of arsenic highly depends on the hadrochemical environment. Chemical conditions control the chemical state (valence) of the ion in solution- here arsenic can occur as either arsenate (As^{+3}) or arsenate (As^{+5}). The chemical behavior of arsenic in groundwater depends on multiple factors including the pH and the relative state of oxidation (i.e., chemically oxidizing or reducing, or 'redox' state). Arsenate (As^{+5}) for example, tends to become more soluble as pH increases. Microbial processes are also known to be involved in the oxidation and mobility of arsenic.[17]

Arsenic concentrations above MCLs currently occur in groundwater in the South Management Area, primarily in wells installed for the Ram's Hill Golf Course. **Figure 12**, from BWD Board presentation by Dudek dated 1/25/2018, shows prior sampling results. Sampling results for the remainder of the Subbasin indicate arsenic to occur at less than half the MCL (5 micrograms per liter [µg/L]). The sampling results for active BWD wells are summarized in **Section 4**.

FIGURE 12



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[17] Sun 2010. The Role of Denitrification on Arsenite Oxidation and Arsenic Mobility in An Anoxic Sediment Column Model with Activated Alumina. In Bioengineering and Biotechnology. https://onlinelibrary.wiley.com/doi/abs/10.1002/bit.22883 This work is cited because it supports that Nitrate, an alternative electron acceptor, can support oxidation of As^{+3} to As^{+5} (arsenate) by denitrifying bacteria in the absence of oxygen. Arsenate is generally considered to be mobile in groundwater at pH levels greater than 8.

3.6.1 Supporting Information Regarding Arsenic

To date all water quality testing has reported 'total arsenic'. While this is consistent with the reporting requirements for drinking water testing, the current monitoring program does not speciate arsenic by valence. The species that occur in groundwater can generally be inferred based on knowledge of water conditions- specifically the pH and Eh (or redox state).

A study of arsenic and nitrate in the Subbasin done in cooperation with the BWD was published by Rezaie-Boroon et al, in 2014.[18] The study was based on data from six BWD wells (ID4-18, ID4-11, ID1-12, ID4-10, ID1-10, and Wilcox) for the period of 2006 to 2014. Their trend analyses are not summarized here because four more years of data have since been collected and the trends have changed. Their work emphasized the following:

- The chemical environment as determined by pH and Eh is important. Both pH and Eh conditions control how dissolved arsenic occurs in aqueous environment (see reference).[19] Arsenic is more soluble in an alkaline (high pH) and anoxic environments. The relative mobility of arsenic depends on its valence, typically occurring as either arsenite (As^{+3}) or arsenate (As^{+5}). As^{+3} is typically more mobile than As^{+5} in anoxic groundwater.
- The presence of iron oxide coatings on soil and sediment particles supports arsenic adsorbtion and can cause the concentration of arsenic in solution to decrease. This will typically occur under oxidizing conditions where As^{+5} will generally occur versus As^{+3}, and where iron oxides will occur.
- *"The most common forms of arsenic in groundwater are their oxy-anions, arsenite (As+3) and arsenate (As^{+5}). Both cations are capable of adsorbing to various subsurface materials, such as iron oxides and clay particles. Iron oxides are particularly important to arsenate fate and transport"* because…*"arsenate [ed: As+5] strongly adsorbs to these surfaces in acidic to neutral waters."* Thus, increases in pH will support the desorption or release of arsenate into groundwater.

The interaction of arsenic with soil and aquifer material containing iron oxide is summarized in a 2015 report by the Water Research Foundation.[20] This study is potentially relevant to the use of arsenic-bearing irrigation water, because it shows that arsenic can be removed from water when passed through soil. The Water Research Foundation report concluded that "Results of this study provide an inexpensive arsenic treatment method for water utilities", while

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[18] Rezaie-Boroon et al, 2014. The Source of Arsenic and Nitrate in Borrego Valley Groundwater Aquifer. Journal of Water Resource and Protection, 5, p1589-1602.
https://www.scirp.org/journal/PaperInformation.aspx?PaperID=51944

[19] Stein, C.L., Brandon, W.C. and McTigue, D.F. (2005) Arsenic Behavior under Sulfate-Reducing Conditions: Beware of the "Danger Zone". EPA Science Forum 2005: Collaborative Science for Environmental Solutions, 16-18 May 2005, Washington DC.

[20] Water Research Foundation, 2015. In-situ Arsenic Removal During Groundwater Recharge Through Unsaturated Alluvium. Web Report #4299.

recognizing that the work was a pilot study and that a good understanding of site conditions is necessary to achieve similar results.

Arsenic may also be released from the dewatering or release of water in from clays. A recent study published in 2018 for the San Joaquin Valley of California examined the potential release of arsenic from the Corcoran Clay, a regionally extensive clay deposit that is being compressed as a result of land subsidence due to groundwater overdraft.[21] Their results "support the premise that arsenic can reside within pore water of clay strata within aquifers and is released due to overpumping".

Four factors were seen to contribute to the occurrence of arsenic in groundwater that included clay thickness, dissolved manganese (Mn) concentrations, elevation (depth), and recent subsidence. As stated in their report "We highlighted four of the most important variables describing arsenic concentration within the Tulare Basin in the recent model, shown in Fig. 2a-d [of their report]. Of these, the thickness of the Corcoran Clay (a confining unit that overlies a lower aquifer) shows a positive correlation with arsenic concentrations due to increased clay content. Elevation has a negative correlation, as lower areas are more likely to have been water-saturated and thus anaerobic. A positive correlation was found between $\log_{10}$(Mn) and arsenic concentrations, as the presence of manganese indicates an anoxic environment, in which arsenic tends to be more soluble. Significantly, recent subsidence from InSAR[22] [ed: land surface elevation data] showed a positive correlation, as over-pumping leads to increased pore water drainage from clays. The first three variables are well-known from the literature and not related to human activity. The quantitative link between pumping-induced subsidence and arsenic concentrations has not been shown before, and is directly related to human activity."

Their analysis supports that geochemical data that include measurements of oxidation-reduction potential (redox) and oxygen content, and testing for minerals that are indicative of geochemical conditions (such as ferrous and ferric iron, and manganese) can support assessment of the potential for arsenic to become mobile in the aquifer system. A recent USGS publication provides further explanation of the role of iron oxides under varying pH and redox conditions (USGS Scientific Investigations Report 2012–5065[23]). A key point made by the USGS is that arsenic becomes mobile at a pH greater than 8 under oxidizing and neutral/transitional

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[21] Overpumping leads to California groundwater arsenic threat. By Ryan Smith, Rosemary Knight, and Scott Fendorf. June 2018. In Nature Communications (2018) 9:2089, DOI: 10.1038/s41467-018-04475, www.nature.com/naturecommunications. or at https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5988660/pdf/41467_2018_Article_4475.pdf

[22] "InSAR (Interferometric Synthetic Aperture Radar) is a technique for mapping ground deformation using radar images of the Earth's surface that are collected from orbiting satellites". see https://volcanoes.usgs.gov/vhp/insar.html

[23] Predicted Nitrate and Arsenic Concentrations in Basin-Fill Aquifers of the Southwestern United States, by David W. Anning, Angela P. Paul, Tim S. McKinney, Jena M. Huntington, Laura M. Bexfield, and Susan A. Thiros; https://pubs.usgs.gov/sir/2012/5065/pdf/sir20125065.pdf

redox conditions, and is potentially mobile under strongly reducing conditions where both arsenite and iron can be in solution.

The USGS Model Report evaluated land subsidence in the Subbasin for the period of the 1960s to 2010 (page 70 of their report) and concluded that "…land subsidence attributed to aquifer-system compaction is not currently a problem in the Borrego Valley and is unlikely to be a significant problem in the future". However, this does not preclude the potential release or extraction of arsenic from clay-rich portions of the aquifer system that may occur under current or future pumping absent subsidence, or as a result of changes in geochemical conditions that could mobilize arsenic from clay-rich sediments that may contain arsenic.

Overall the occurrence, nature, and extent of arsenic in the Subbasin is not well understood. It is more prevalent in South Management Area wells. While currently water quality conditions are good relative to arsenic, it was observed to be at or near drinking water MCLs in multiple BWD water supply wells during the last decade and could affect BWD's water supply in the future.

3.7 Correlations Among Water Quality Parameters (Combined Data Assessment)

One of the goals of this Report is to evaluate whether multiple chemical parameters can be used to better define and predict COC trends at BWD water supply wells. Piper diagrams presented in **Section 3.2** were used to examine spatial trends and also illustrate that there are definable relationships among the general minerals seen in the trilinear diagrams. In this section the water chemistry data are combined for all wells to examine general relationships and correlations. The data set also includes pH, hardness. Other potentially important geochemical parameters such as iron and manganese were not included because they were not uniformly obtained for the water quality samples historically collected.

3.7.1 Water Quality Data Correlations

Water quality data obtained since 2004 were used to examine potential correlations and relationships. The recent data were selected to represent current conditions as water quality has changed over time in many wells. Among the parameters that were tested include anions (HCO_3, Cl, SO_4), cations (Ca, Mg, and Na [potassium was not included as less data were collected]), pH, TDS, Ca+ Na, Cl+HCO_3, As, F, and NO_3. Also included in the correlation analysis were two parameters named Midst and Low Sat that represented the percentage of well screen open to flow per aquifer unit as described in each of the wells (for example if a well is completed with the same amount of screen length per aquifer then both values would be 50 percent).

Correlations greater than 0.5 or less than -0.5 are highlighted in **Table 3**. Values between 0.5 and 0.7 are underlined, and values greater than 0.7 are in bold. The South Management Area data have been separated from the North and Central Management Areas.

Selected data are shown in graphical form in this section. The data set used in the correlations was limited to those samples where the general minerals charge balance was within 10 percent. The graphs further restrict the data to only include higher quality data with a +/- 5 % charge balance. Hem (1985) considers data with 5% charge balance to be of good quality[24].

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[24] John Hem, 1985. Study and Interpretation of the Chemical Characteristics of Natural Water. USGS Water-Supply Paper 2254. From page 163: "Under optimum conditions, the analytical results for major constituents of water have an accuracy of +/-2 - +/- 10 percent. That is, the difference between the reported result and the actual concentration in the sample at the time of analysis should be between 2 and 10 percent of the actual value. Solutes present in concentrations above 100 mg/L generally can be determined with an accuracy of better than +/- 5 percent. Limits of precision (reproducibility) are similar."

Table 3

NORTH and CENTRAL

	Bicarbonate	Chloride	Sulfate	Fluoride	Calcium	Magnesium	Sodium			cation	anion	pct middle	pct lower	Arsenic	Nitrate
	HCO3	**Cl**	**SO4**	**F**	**Ca**	**Mg**	**Na**	**pH**	**TDS**	**Ca+Na**	**Cl+HCO3**	**MidSat**	**LowSat**	**As**	**NO3**
HCO3	1.00	**0.73**	-0.38	-0.30	0.46	**0.76**	-0.10	-0.69	0.27	0.18	**0.94**	-0.48	0.30	-0.28	0.49
Cl		1.00	-0.26	-0.09	0.28	0.54	0.31	-0.53	0.43	0.36	**0.92**	-0.40	0.15	-0.13	**0.72**
SO4			1.00	0.26	0.46	0.07	0.67	0.16	**0.70**	**0.70**	-0.35	0.01	0.09	0.23	-0.43
F				1.00	-0.30	-0.23	0.54	0.48	0.15	0.21	-0.21	-0.43	0.47	0.66	-0.14
Ca					1.00	**0.79**	0.34	-0.60	**0.72**	**0.77**	0.40	-0.31	0.25	-0.32	0.14
Mg						1.00	0.23	**-0.75**	0.57	0.58	**0.70**	-0.48	0.40	-0.33	0.37
Na							1.00	0.03	**0.83**	**0.86**	0.10	-0.39	0.38	0.31	0.22
pH								1.00	-0.31	-0.30	-0.65	0.24	-0.12	0.68	-0.46
TDS									1.00	**0.95**	0.37	-0.41	0.33	0.04	0.21
Ca+Na										1.00	0.28	-0.43	0.39	0.04	0.23
Cl+HCO3											1.00	-0.47	0.24	-0.23	0.65
MidSat												1.00	**-0.86**	-0.30	-0.43
LowSat													1.00	0.30	0.22
As														1.00	-0.18
NO3															1.00

SOUTH

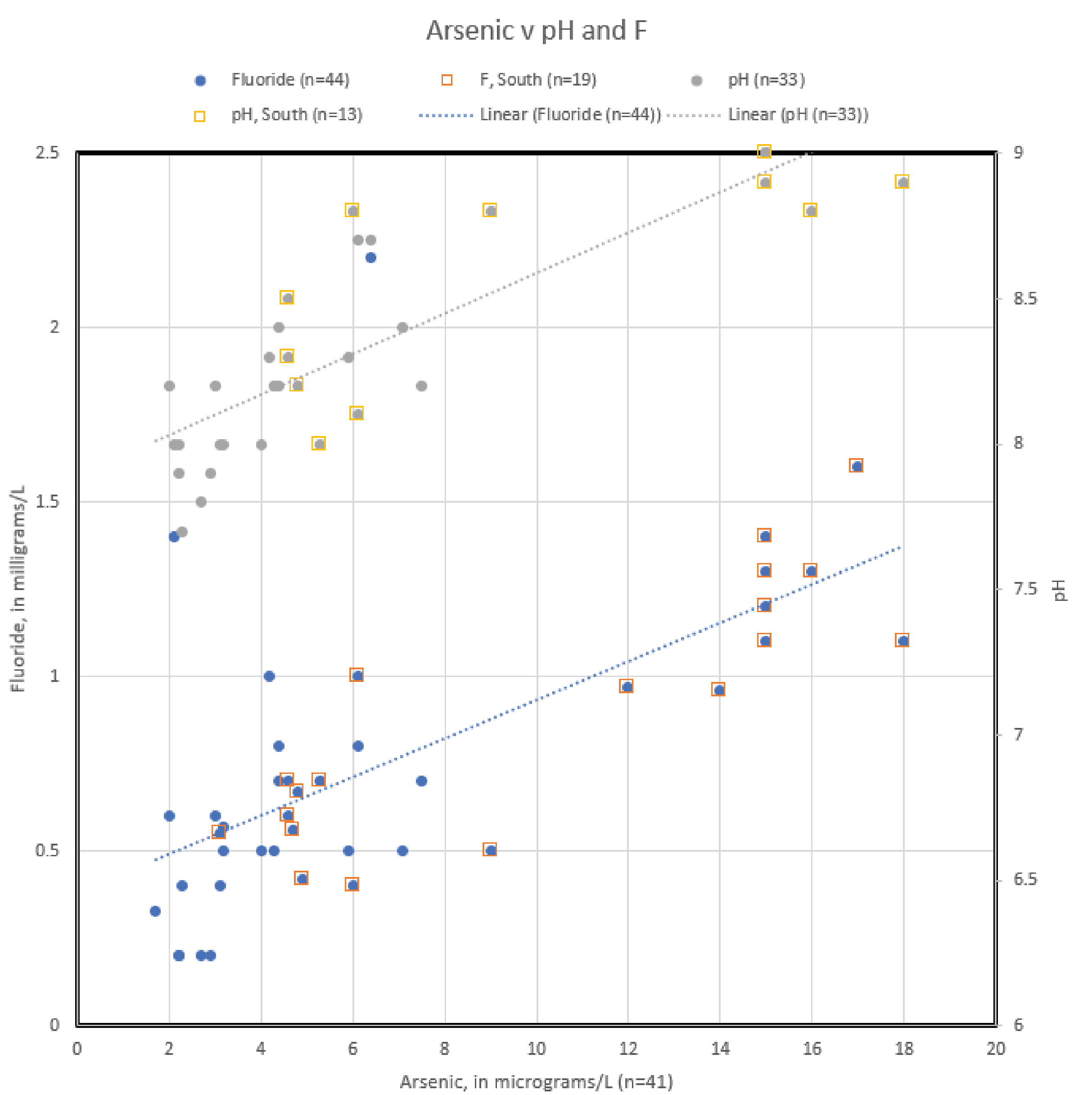
	Bicarbonate	Chloride	Sulfate	Fluoride	Calcium	Magnesium	Sodium					pct middle	pct lower	Arsenic	Nitrate
	HCO3	**Cl**	**SO4**	**F**	**Ca**	**Mg**	**Na**	**pH**	**TDS**	**Ca+Na**	**Cl+HCO3**	**MidSat**	**LowSat**	**As**	**NO3**
HCO3	1.00	-0.45	-0.44	0.14	-0.37	**-0.31**	-0.16	0.27	-0.33	-0.25	0.14	0.31	-0.33	0.10	0.19
Cl		1.00	**0.87**	-0.31	**0.80**	0.36	**0.83**	-0.34	**0.92**	**0.84**	0.47	0.17	-0.19	-0.08	0.11
SO4			1.00	-0.37	**0.95**	0.46	**0.73**	-0.31	**0.96**	**0.86**	0.37	-0.03	0.04	-0.01	0.01
F				1.00	-0.48	-0.16	-0.14	0.56	-0.40	-0.41	-0.33	-0.23	0.23	**0.73**	-0.22
Ca					1.00	0.42	0.60	-0.46	**0.92**	**0.78**	0.29	0.05	-0.05	-0.13	0.08
Mg						1.00	-0.03	**-0.13**	0.42	0.16	0.07	-0.11	0.11	0.06	-0.05
Na							1.00	-0.10	**0.81**	**0.86**	0.49	0.24	-0.24	0.09	0.19
pH								1.00	-0.35	-0.25	-0.13	-0.18	0.19	0.55	-0.30
TDS									1.00	**0.89**	0.44	0.14	-0.14	-0.03	0.18
Ca+Na										1.00	**0.70**	0.18	-0.19	-0.06	0.15
Cl+HCO3											1.00	0.27	-0.30	-0.14	0.05
MidSat												1.00	-1.00	-0.15	0.46
LowSat													1.00	0.17	-0.45
As														1.00	-0.06
NO3															1.00

COC	North and Central	South
Arsenic	pH (.68), F (.66)	F (.73), pH (.55)
Nitrate	Cl (.72)	-none-
Sulfate	TDS (.70), Na (.67)	TDS (.96), Ca (.95), Cl (.87), Na (.73)
Fluoride	As (.66), Na (.54)	As (.73), pH (.56)
TDS	Na (.83), Ca (.72), SO_4 (.70), Mg (.57)	SO_4(.96), Cl (.92), Ca (.92), Na (.81)

Arsenic and Fluoride

Arsenic and fluoride concentrations are correlated and both increase with pH. **Figure 13** depicts arsenic versus fluoride and pH. (pH versus As is in the upper portion of the graph and the y-axis label is to the right; fluoride versus As is in the lower portion and the y-axis is to the left). In both cases the correlations are influenced by the higher arsenic concentrations observed in the South Management Area (as noted by squares drawn around the data points). Every occurrence of arsenic above the MCL of 10 µg/L is associated with pH values greater than 8.5 (upper portion of the graph).

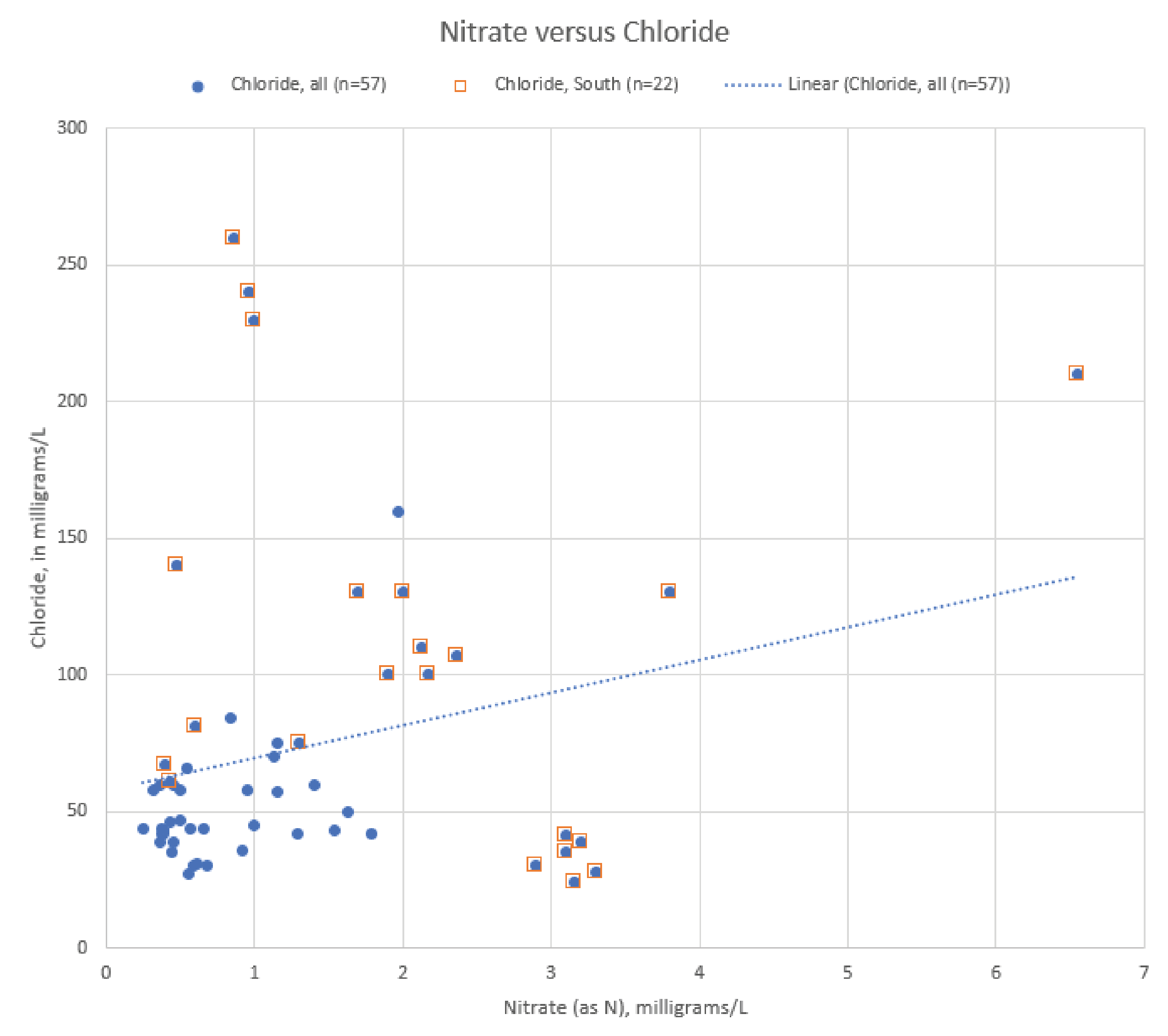
FIGURE 13



Nitrate

Nitrate had few water quality parameter correlations. Nitrate versus chloride is depicted in **Figure 14**. While there was a statistically-indicated correlation in **Table 3** for the North and Central Management Areas, chloride does not appear to be a globally useful predictor of nitrate.

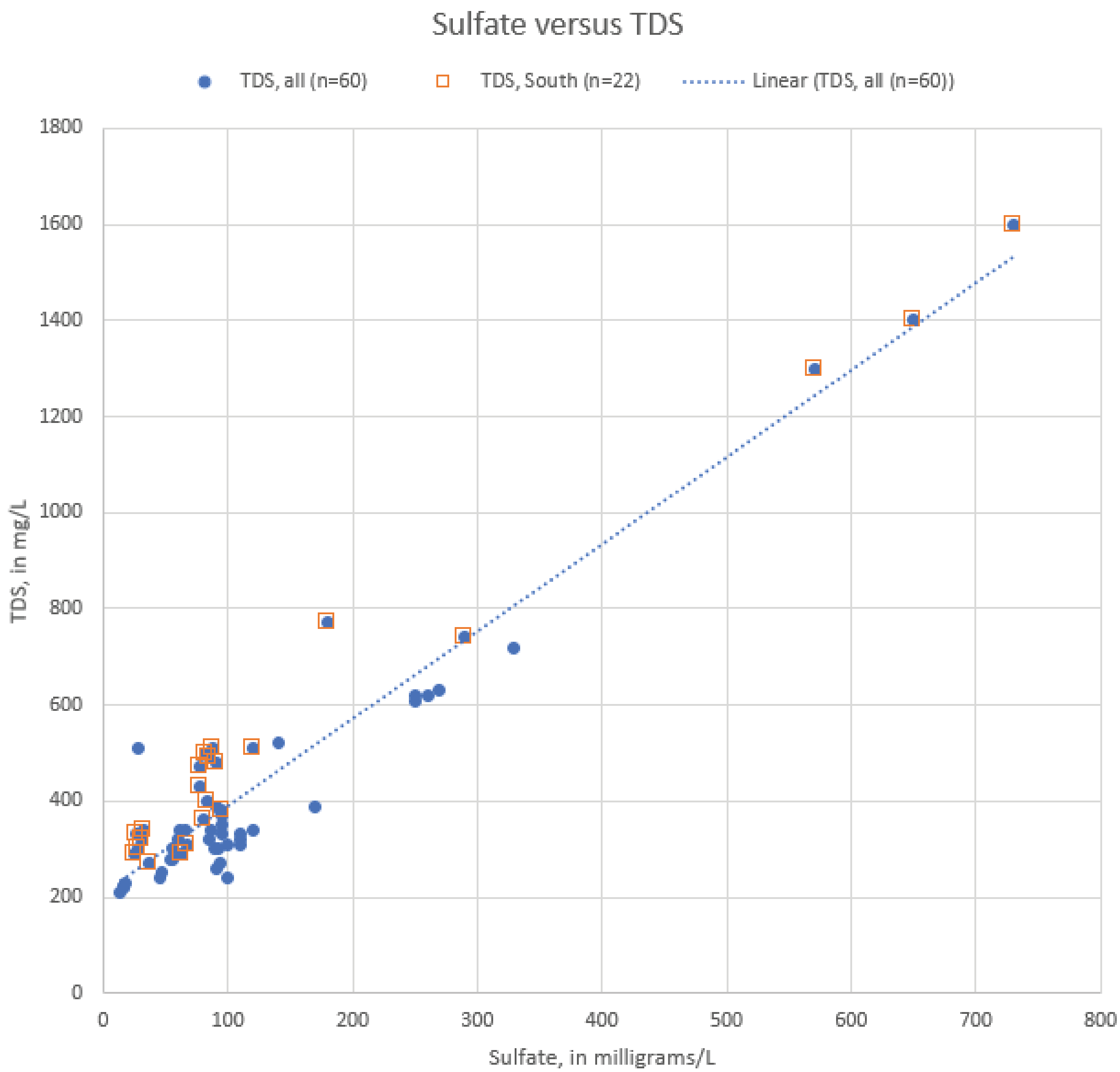
FIGURE 14



Sulfate

The correlation of sulfate with TDS is depicted in **Figure 15**. The three high sulfate values (> 500 mg/L) from the South Management Area strongly influence the correlation.

FIGURE 15

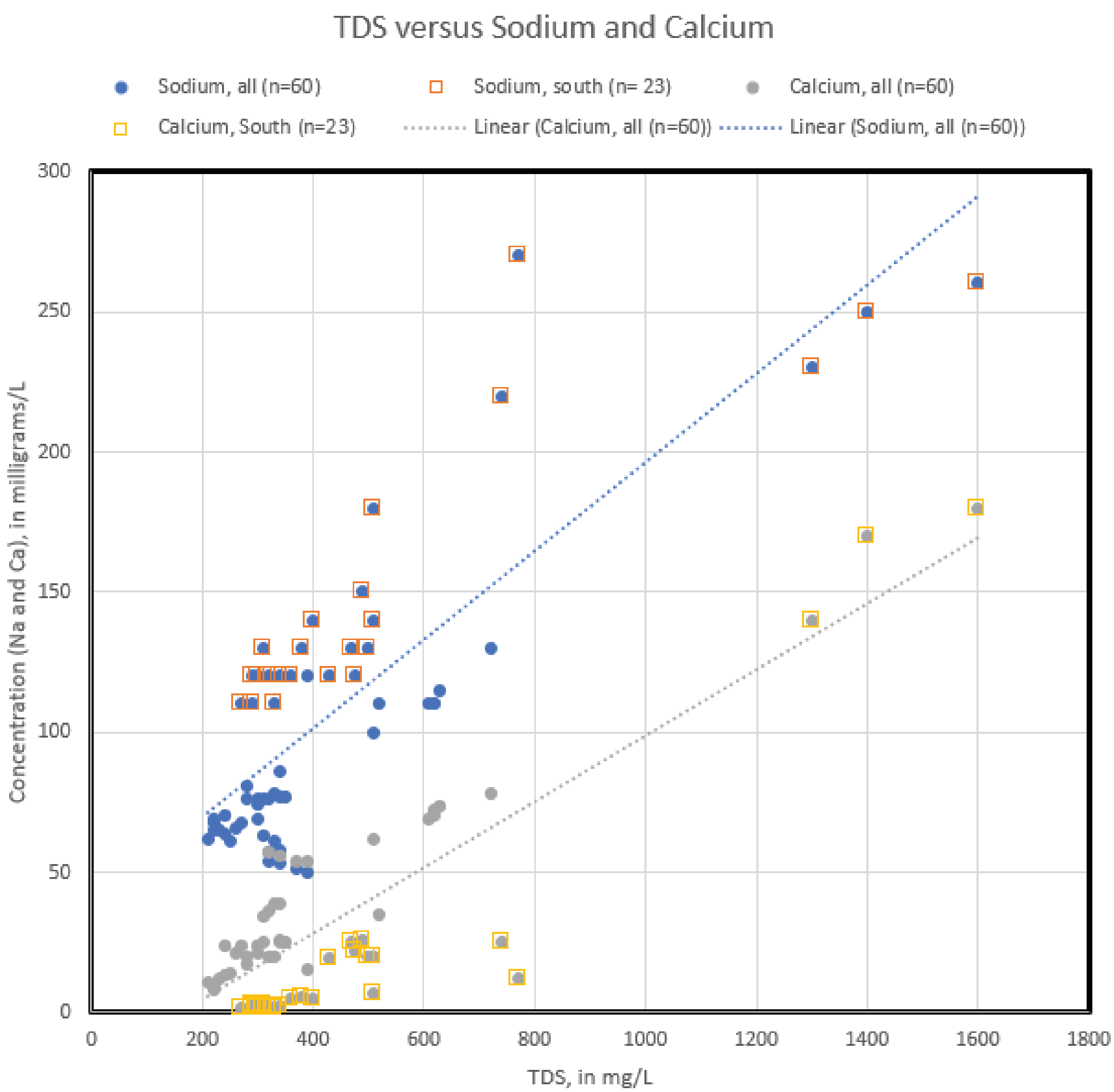


TDS

Multiple analytes correlated with TDS. Sulfate is shown in the previous figure. Sodium and calcium are shown versus TDS in **Figure 16**, and chloride versus TDS is shown in **Figure 17**. Both figures show that the South Management Area water chemistry is different than that observed to the north. The regression lines in **Figure 16** effectively split the two sets of data by management area.

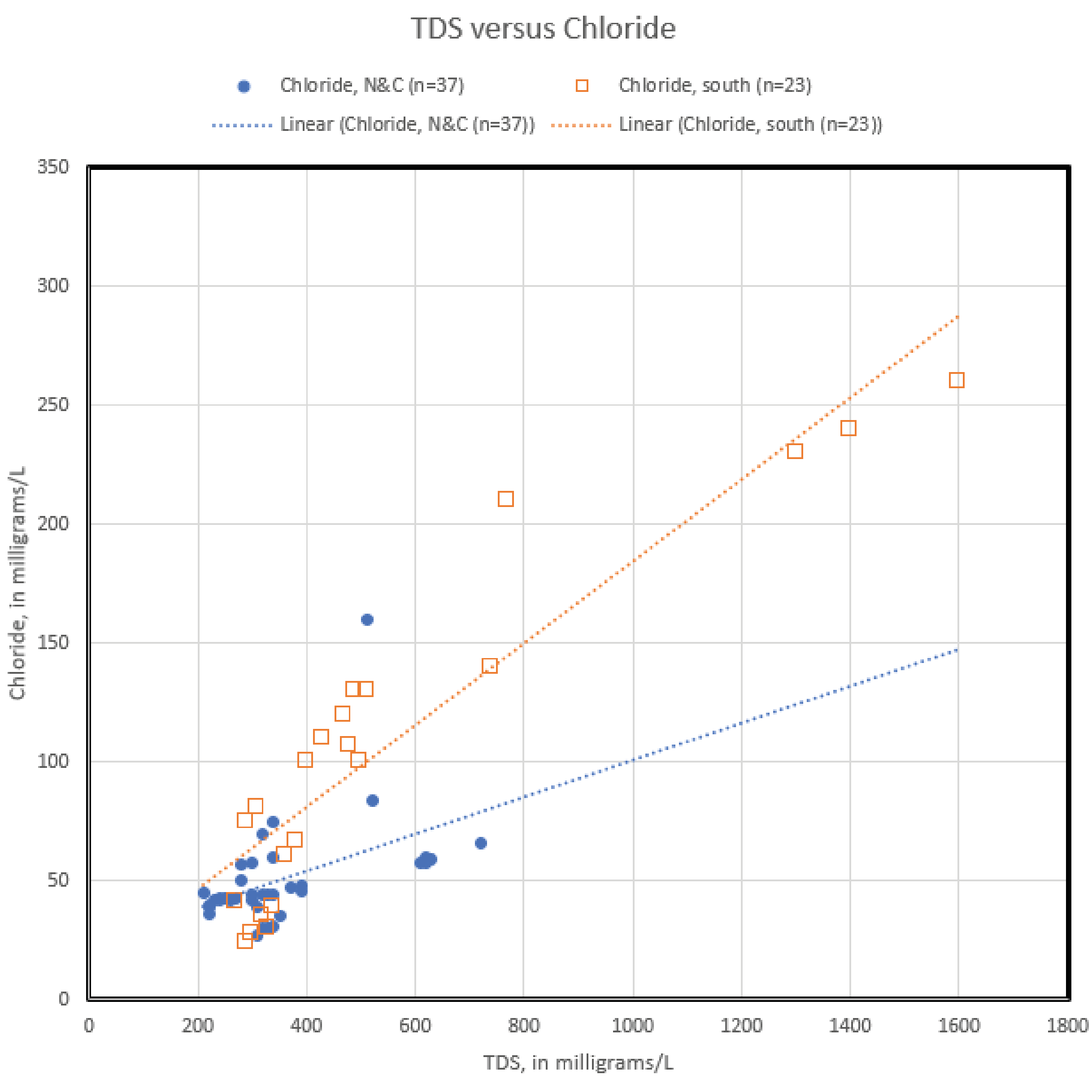
While correlations exist for all three analytes, sodium and chloride represents a higher percentage of TDS and calcium represents a smaller percentage of TDS in the South Management Area.

FIGURE 16



Chloride data segregated by management area are depicted in **Figure 17**. The highest chloride concentrations typically occur in the South Management Area.

FIGURE 17



3.8 General Minerals: Summary of Observations

A summary of the Piper diagram analyses for the 23 wells used in this Report is included in **Table 1B**.

- Water quality has clearly changed over time. Of the 23 wells, six had insufficient general minerals data to assess trends. Of the 17 wells with sufficient temporal data, approximately 70 percent showed a change in natural water chemistry over time.
- Sulfate is the general mineral most commonly observed to be increasing in groundwater (as a relative percentage per the Piper diagrams).
- Groundwater quality systematically varies with distance along the valley, with water in the South Management Area being noticeably different. Here the well data were not differentiated by aquifer or relative depth

Five COCs are included in this Report. Nitrate and arsenic are currently the chemical of highest concern specific to BWD drinking water quality. Fluoride, sulfate, and TDS are other three COCs. The data were collected over varying time periods and not all sampling events included a complete set of the eight general minerals. A review of the COCs for all of the active BWD wells is provided in **Section 4**.

Limited depth-specific hydraulic and contaminant data are available to assess the nature and extent of COCs in groundwater. As a result, the analyses among wells is limited to spatial comparisons. The lack of depth-specific data is a data gap that affects the assessment of all water quality parameters. The primary impact of this data gap is that the depth-dependent data will provide a good indication of how water quality will change over time as water levels decline. If specific zones are contributing poor water quality, then the data can be used to selectively complete future water wells to reduce the impact of the inflow of poor water quality.

4.0 CHEMICALS OF CONCERN (COCs) AT BWD WATER SUPPLY WELLS

The five chemicals of concern (COCs) include arsenic, total dissolved solids, nitrate, sulfate, and fluoride (As, TDS, NO_3, SO_4, and F). There are nine BWD water supply wells reviewed here. The COC and Piper diagram data for these wells is depicted in the following Figures that follow this subsection:

Figure 18 ID4-4 (Well #4, as depicted in Figure 4)
Figure 19 ID4-11 (Well #5, as depicted in Figure 4)
Figure 20 ID4-18 (Well #2, as depicted in Figure 4)
Figure 21 ID1-10 (Well #14, as depicted in Figure 4)
Figure 22 ID1-12 (Well #9, as depicted in Figure 4)
Figure 23 ID1-16 (Well #12, as depicted in Figure 4)
Figure 24 ID5-5 (Well #8, as depicted in Figure 4)
Figure 25 Wilcox (Well #13, as depicted in Figure 4)
Figure 26 ID1-8 (Well #15, as depicted in Figure 4)

Of these, three wells are being considered for replacement- ID4-4, ID4-18, and ID1-10. **Table 4** summarizes the review of **Figures 18 through 26**.

Water quality trends, if identified, are based on visual description of the various data. The GSP describes the use of Mann-Kendall statistical trend analyses, a non-parametric way to detect a monotonic trend (up or down), to assess individual water quality parameters. The work here is focused on identifying correlations among parameters.

NOTE: Well ID4-4 was redrilled in 1979. Water chemistry changed.

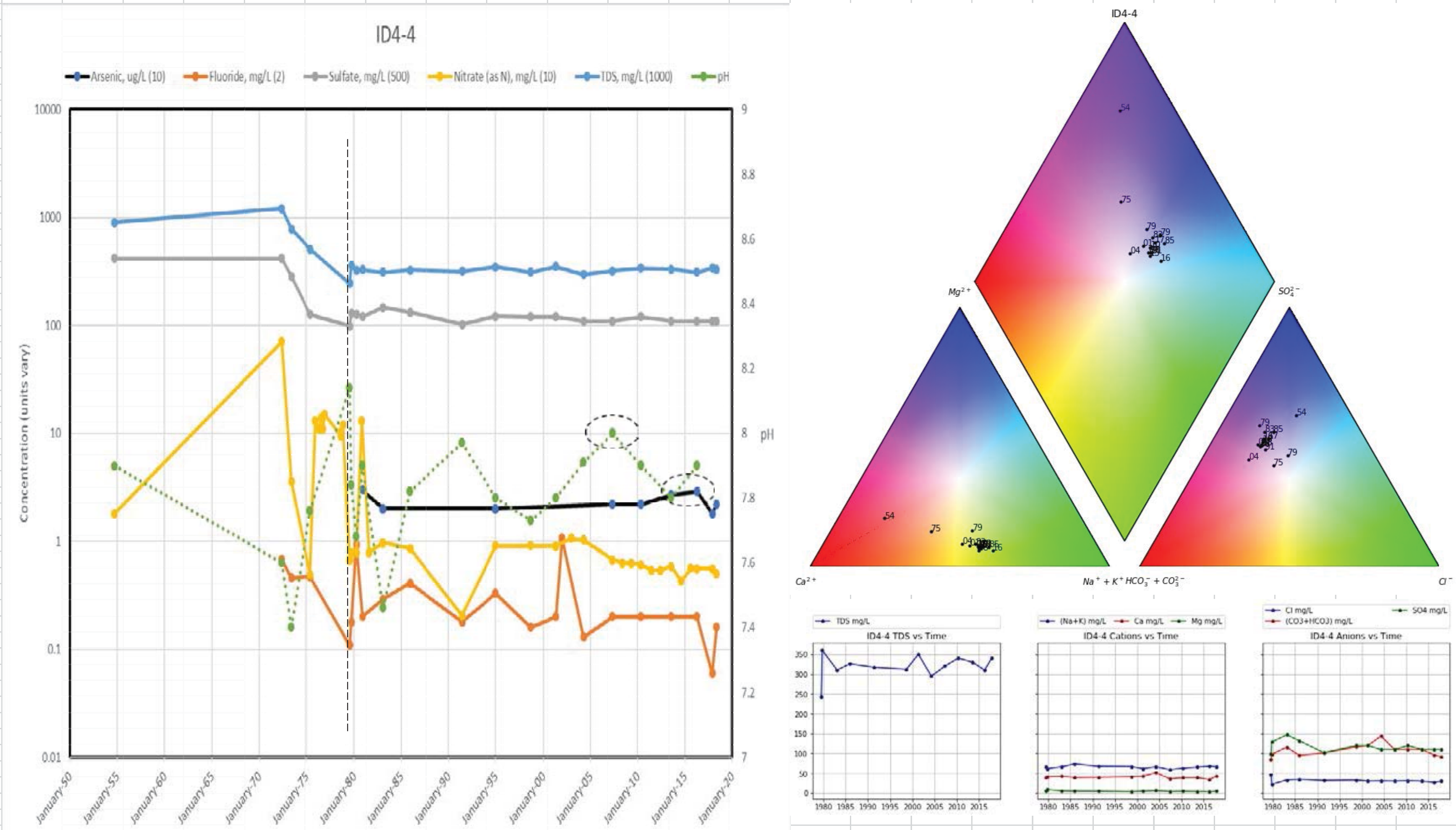


FIGURE 18. BWD Well ID4-4

Notes: pH and COC concentrations versus time shown left panel.
Piper trilinear diagram depicts change over time- the labels indicate the last two digits of the year when sampled (e.g. 72 = 1972)

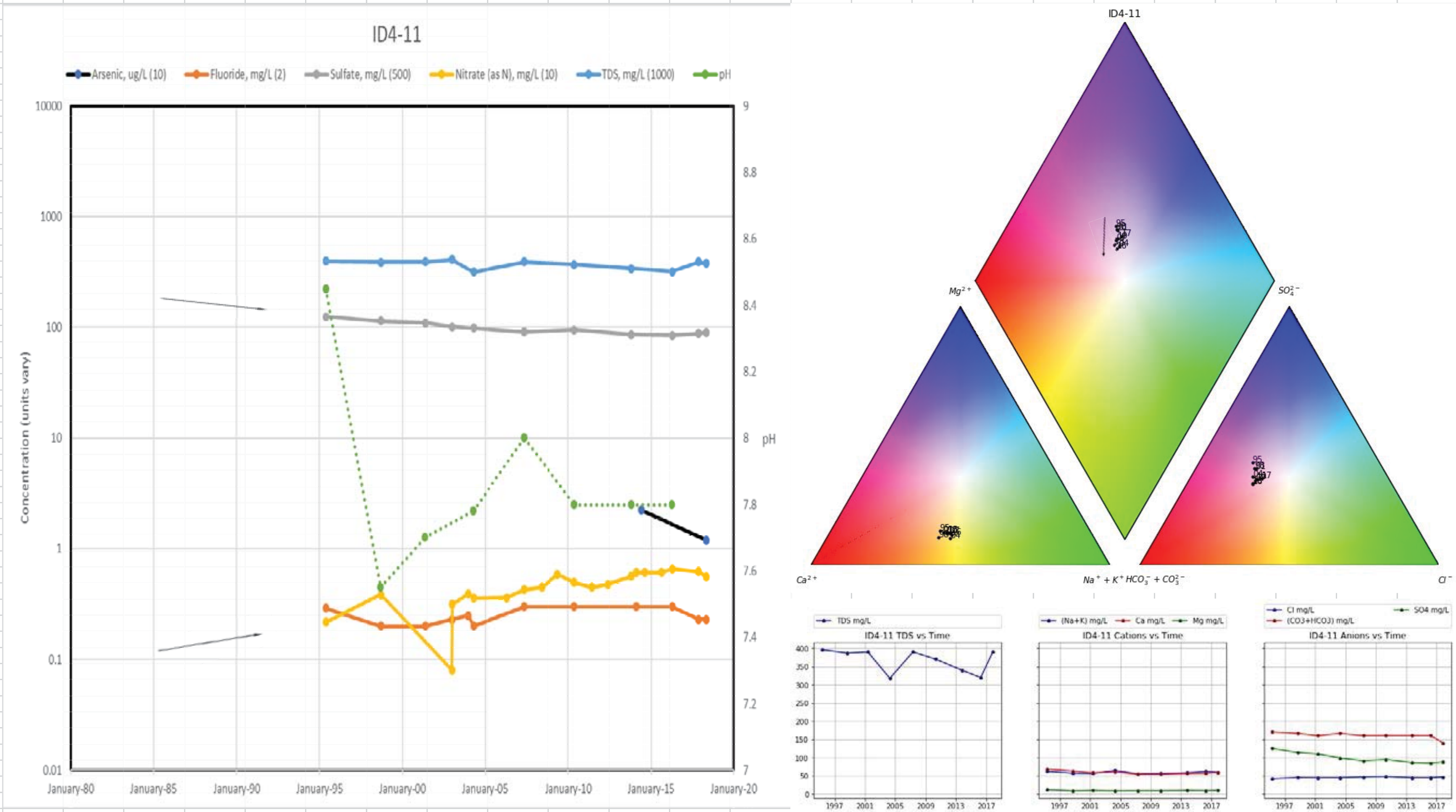


FIGURE 19. BWD Well ID4-11

Notes: pH and COC concentrations versus time shown left panel.
Piper trilinear diagram depicts change over time- the labels indicate the last two digits of the year when sampled (e.g. 72 = 1972)

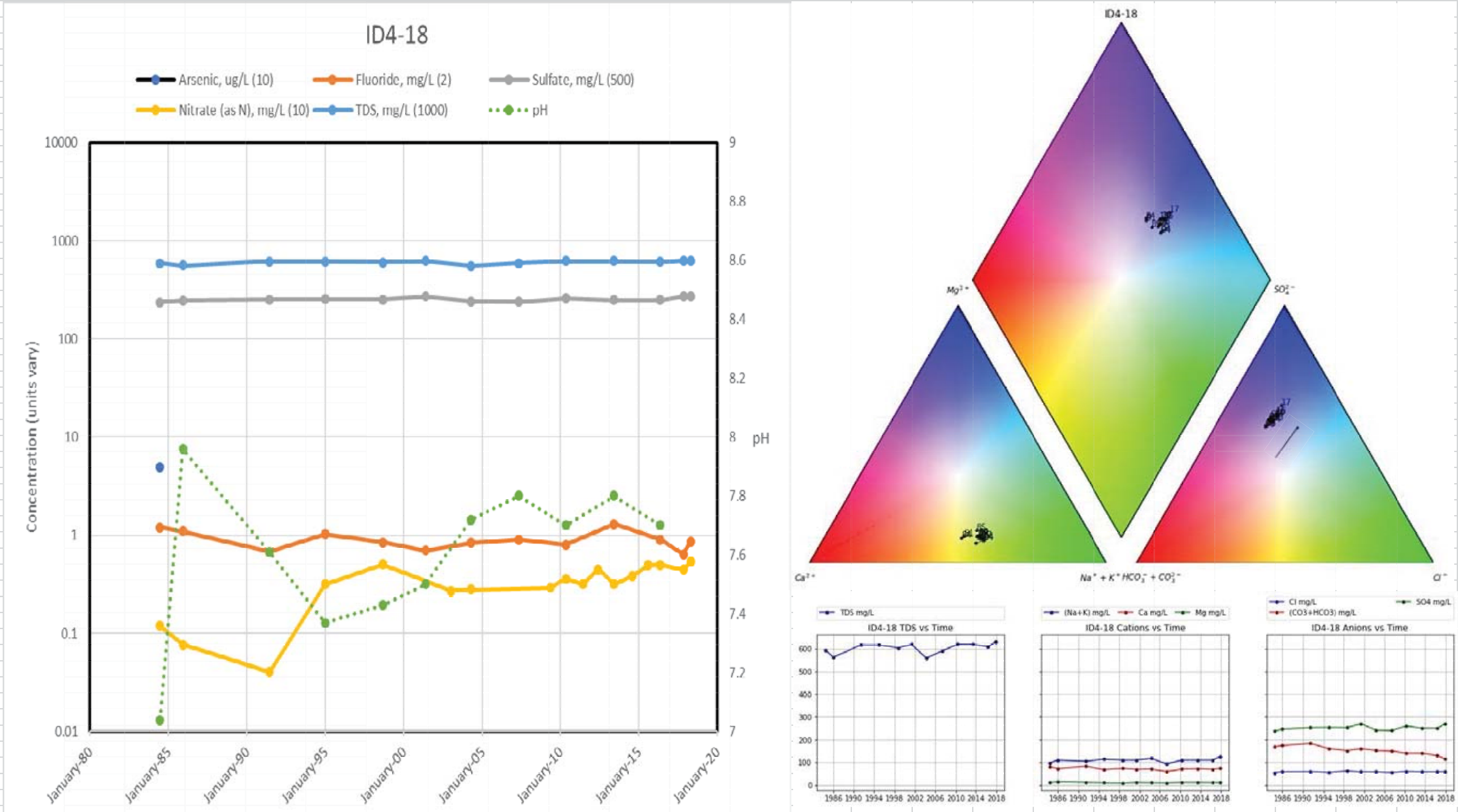


FIGURE 20. BWD Well ID4-18

Notes: pH and COC concentrations versus time shown left panel.

Piper trilinear diagram depicts change over time- the labels indicate the last two digits of the year when sampled (e.g. 72 = 1972)

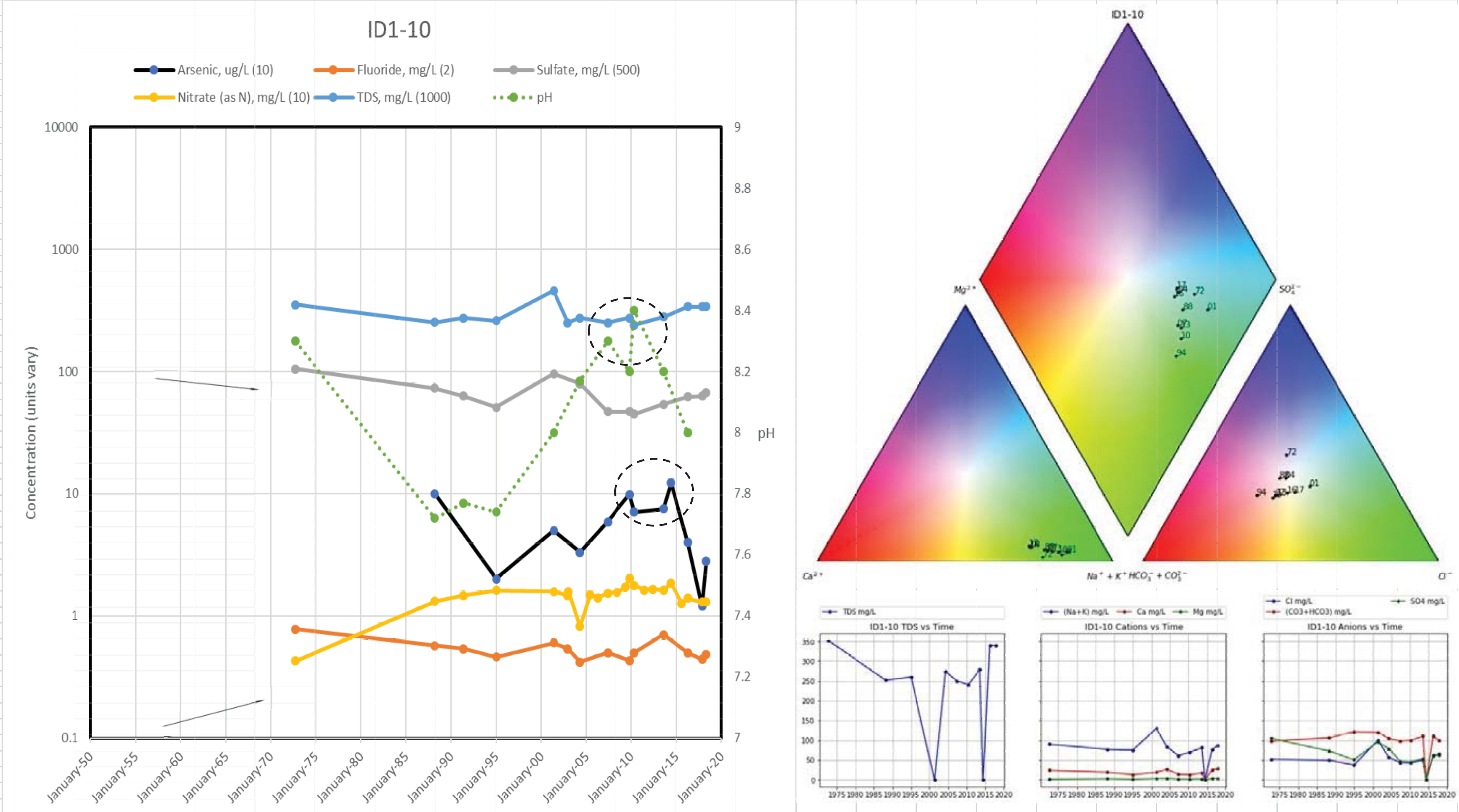


FIGURE 21. BWD Well ID1-10

Notes: pH and COC concentrations versus time shown left panel.
Piper trilinear diagram depicts change over time- the labels indicate the last two digits of the year when sampled (e.g. 72 = 1972)

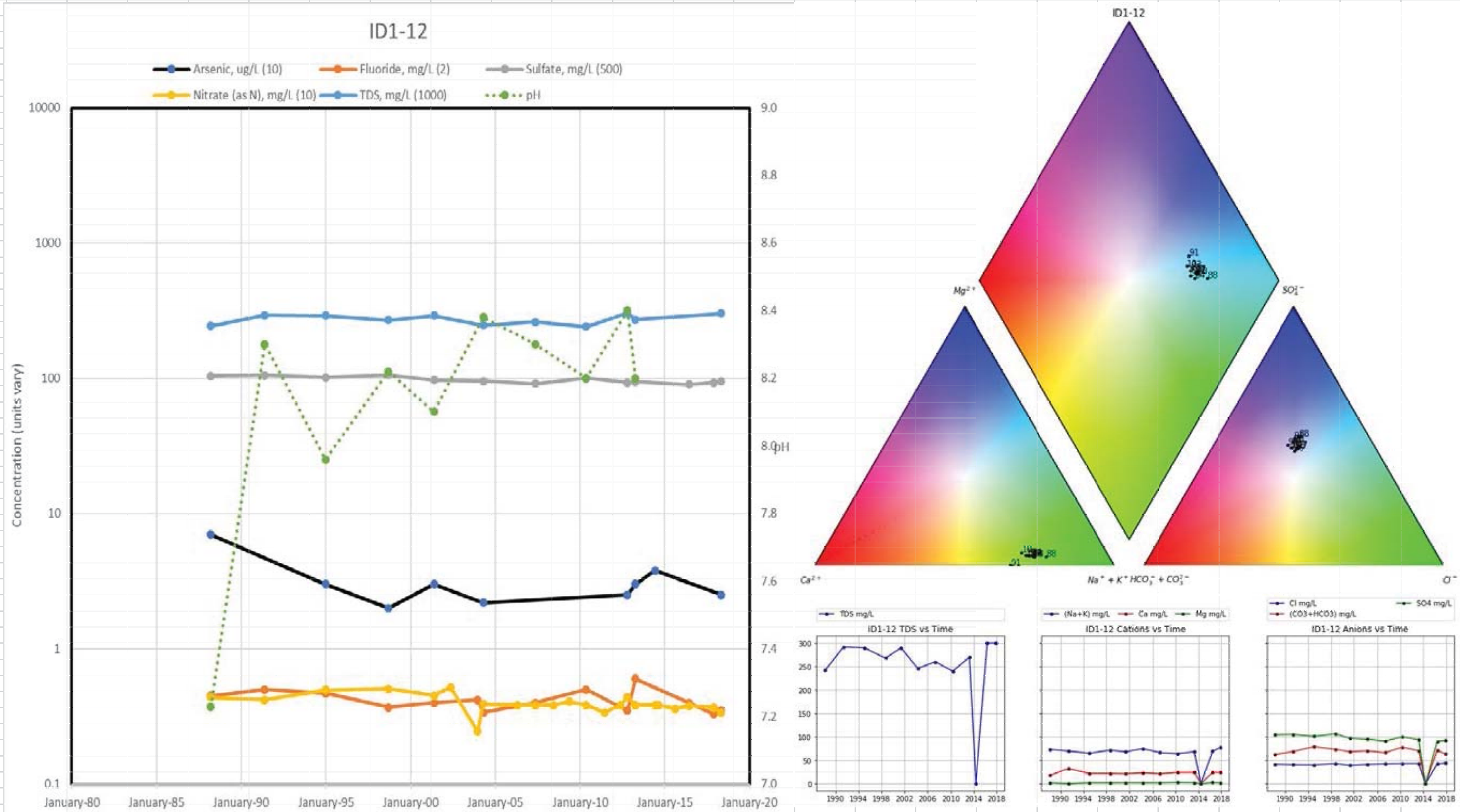


FIGURE 22. BWD Well ID1-12

Notes: pH and COC concentrations versus time shown left panel.

Piper trilinear diagram depicts change over time- the labels indicate the last two digits of the year when sampled (e.g. 72 = 1972)

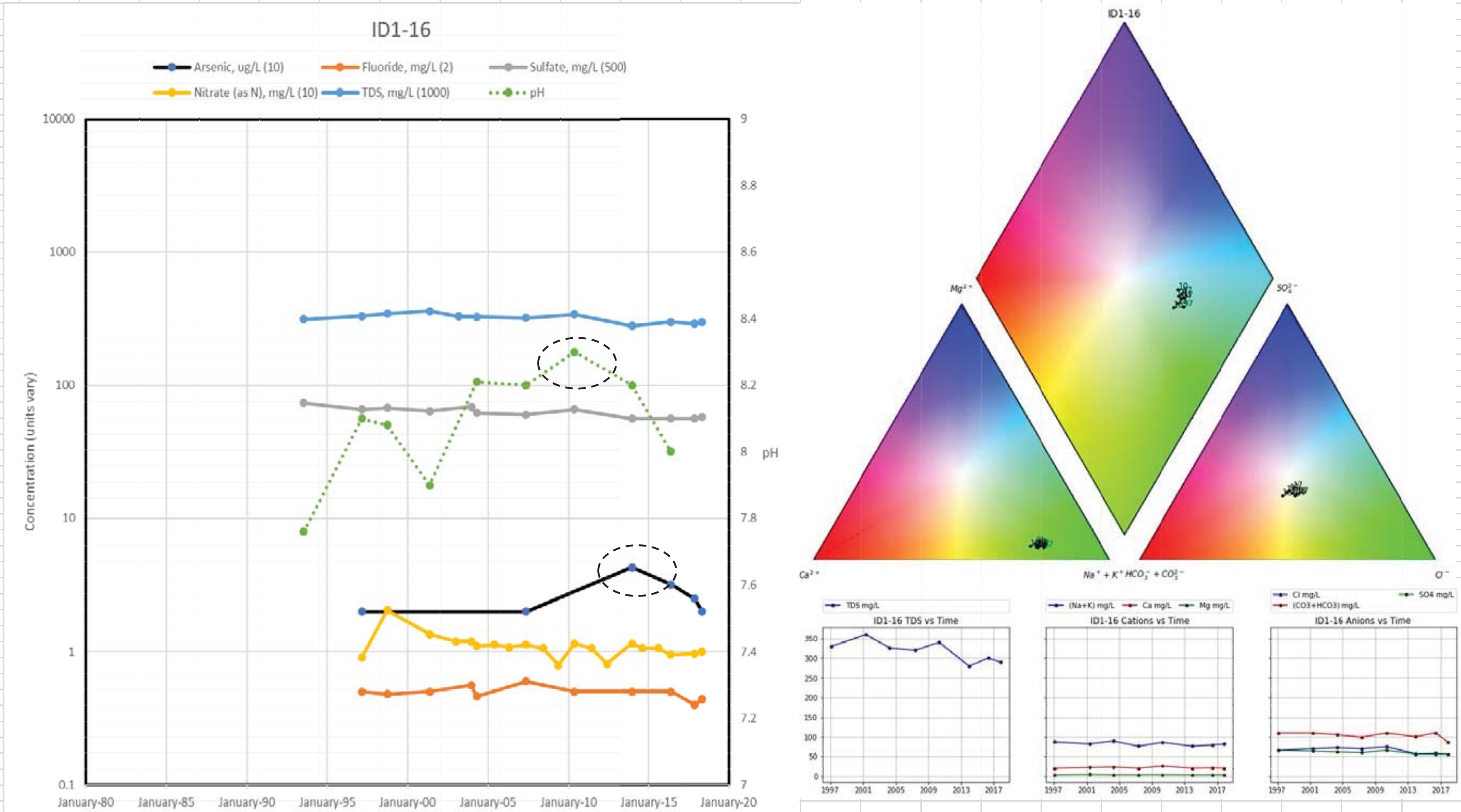


FIGURE 23. BWD Well ID1-16

Notes: pH and COC concentrations versus time shown left panel.
Piper trilinear diagram depicts change over time- the labels indicate the last two digits of the year when sampled (e.g. 72 = 1972)

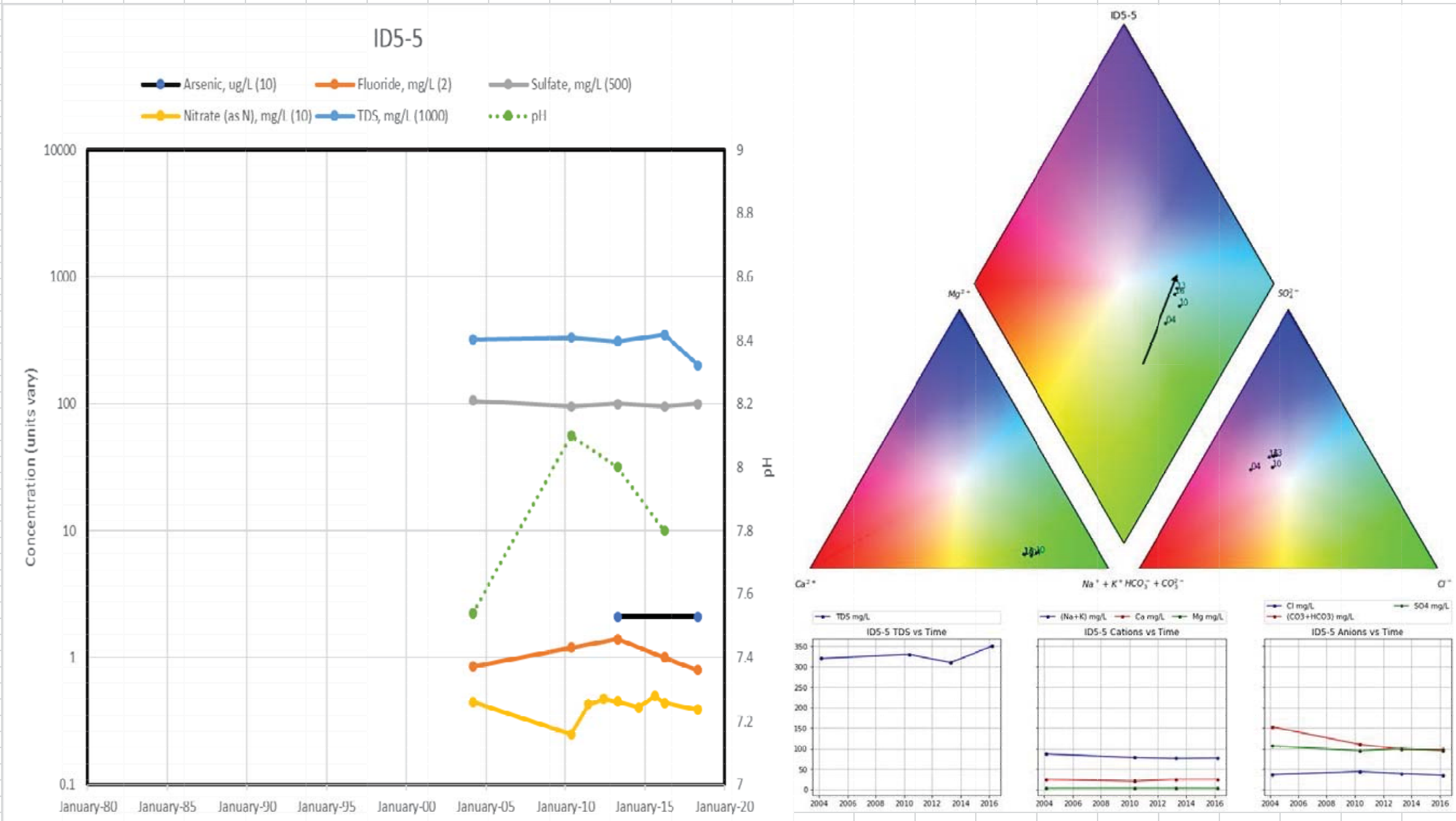


FIGURE 24. BWD Well ID5-5

Notes: pH and COC concentrations versus time shown left panel.
Piper trilinear diagram depicts change over time- the labels indicate the last two digits of the year when sampled (e.g. 72 = 1972)

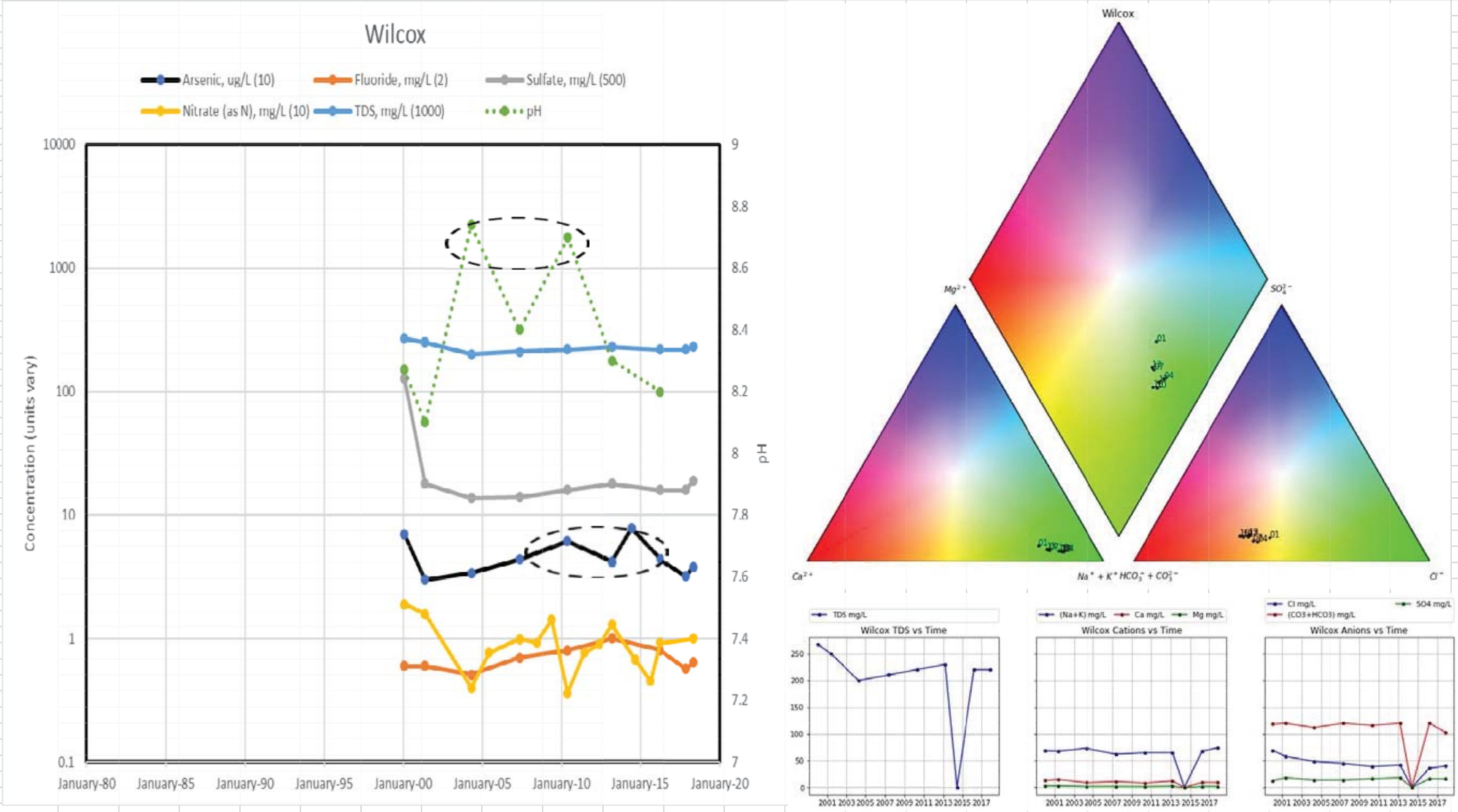


FIGURE 25. BWD Wilcox Well

Notes: pH and COC concentrations versus time shown left panel.
Piper trilinear diagram depicts change over time- the labels indicate the last two digits of the year when sampled (e.g. 72 = 1972)

FIGURE 26. BWD Well ID1-8

Notes: pH and COC concentrations versus time shown left panel.
Piper trilinear diagram depicts change over time- the labels indicate the last two digits of the year when sampled (e.g. 72 = 1972)

TABLE 4

WELL	TDS/ Gen Min (MCL: 500 recc/1000 max, mg/L)	Sulfate (MCL: 250 recc/500 max,mg/L)	Arsenic (MCL: 10 ug/L)	pH	Nitrate (MCL: 10 mg/L as N)	Fluoride (MCL: 2 mg/L)
ID4-4 (#4)**	Stable (330) TDS: 320 to 340 GenMins*: Vble, cation trend may develop	Stable (110) SO4: 110 to 120	In Range (2.2) As: 1.8 to 2.9	Stable Range pH*: 7.8 to 8	Decreasing (0.5) NO3: 1.0 to 0.43	In Range (0.16) 0.6 to 0.2
ID4-11 (#5)	Stable (380) TDS: 320 to 390 GenMins*: Vble, anion trend may develop	Stable SO4: 91 to 95 Was decreasing prior to 2005	Insuff. Data (2.1) As: 1.2 to 2.2 Two recent detects	Stable Range pH*: 7.8 to 8	Increasing (0.56) NO3: 0.36 to 0.66	In Range (0.23) 0.23 to 0.3
ID4-18 (#2)**	Possibly Increasing (630) TDS: 590 to 630 GenMins: inc SO4, dec HCO3	Increasing (**270**) SO4: 240 to 270 Slowly changing	Non-Detect	Stable Range pH*: 7.7 to 7.8	Increasing (0.54) NO3: 0.29 to 0.54	In Range (0.87) 0.54 to 1.3
ID1-10 (#14)**	Possibly Increasing (340) TDS: 250 to 340 GenMins: inc SO4, dec HCO3 (major changes since 1972)	Increasing (67) SO4: 45 to 67 Slowly changing	In Wide Range (2.8) As: 1.2 to **12.2** Maximum 6/2014	In Wide Range pH*: 8.0 to 8.4 Maximum 5/2010 (*~2 yr ahead of As*)	In Range (1.3) NO3: 1.27 to 2.02	In Range (0.48) 0.43 to 0.7
ID1-12 (#9)	Stable (300) TDS: 260 to 300 GenMins: Stable	Stable (95) SO4: 91 to 95	In Range (2.5) As: 2.5 to 3.79	In Range pH*: 8.2 to 8.4	In Range (0.34) NO3: 0.34 to 0.44	In Range (0.34) 0.38 to 0.6
ID1-16 (#12)	Possibly Decreasing (340) TDS: 280 to 340 GenMins: SO4 slowly decreasing	Decreasing (58) SO4: 56 to 66 Slowly changing	In Range (2.0) As: 2.0 to 4.3 Maximum 12/2013	In Range pH*: 8.0 to 8.3 Maximum 5/2010 (*~3 yr ahead of As*)	In Range (1.3) NO3: 1.27 to 2.02	In Range (0.48) 0.43 to 0.7
ID5-5 (#8)	Stable (350) TDS: 202 to 350 GenMins*: Vble, anion trend may develop (inc SO4)	Stable (100) SO4: 95 to 106	Insuff. Data (2.1) As: 2.1 (twice) Two recent detects	In Wide Range pH*: 7.54 to 8.1	In Range (0.39) NO3: 0.25 to 0.50	In Range (0.8) 0.85 to 1.4
Wilcox (#13)	Stable (230) TDS: 210 to 230 GenMins: SO4 slowly increasing	Increasing (19) SO4: 14 to 19 Slowly changing	In Range (3.8) As: 3.2 to 7.8 Maximum 6/2014	In Range pH*: 8.2 to 8.7 Maximum 5/2010 (*~4 yr ahead of As*)	In Range (1.0) NO3: 0.36 to 1.42	In Range (0.64) 0.57 to 0.87
ID1-8 (#15)	Possibly Increasing (460) TDS: 430 to 510 GenMins: long-term inc SO4 & Cl & Ca, dec HCO3 (major changes since 1972)	Stable (86) SO4: 82 to 110	In Range (4.0) As: 3.1 to 6.8 Maximum 5/2010	In Range pH*: 8.0 to 8.4 Maximum during 2004 to 2007 (*~3 to 6 yr ahead of As*)	In Range (1.6) NO3: 1.6 to 2.46 (long-term inc)	In Range (0.62) 0.55 to 1.0

Notes:
* Most recent general minerals and pH analyses done in 2016
** Wells expected to be replaced or re-drilled in short-term

Explanation:
Trends noted as Stable, Increasing, Decreasing, Possibly Increasing/Decreasing, or In a Range
Number after descriptor – e.g. Stable (330), is the most recent sampling result from Spring 2018
Next line is the range of values observed since 2005
GenMins refers to the set of general minerals data- eight major anions and cations
xx, a value that is highlighted occurs at a concentration greater than 50% of the MCL
xx, a value that is highlighted and bold occurs at a concentration greater than the MCL

4.1 North Management Area (3 Wells: ID4-4, ID4-11, and ID4-18)

The North Management Area wells are generally located to the west and upgradient of the irrigated agricultural areas visible in **Figures 4 and 7**. COC-specific observations are included in **Table 4**.

ID4-4

ID4-4 was re-drilled in 1979 due to high nitrate concentrations related to the upper aquifer. Nitrate remains detectable but at low concentrations. Water quality is good and reasonably stable. The District is currently planning to re-drill this well at the same site as a result of poor well conditions that resulted in sanding and the installation if a well liner that limits the depth to which the pump can be installed in the well.

Additional information regarding the well replacement can be found in a 8/30/2018 Dudek presentation entitled "Water Vulnerability & New Extraction Well Site Feasibility Analysis" posted at the County SGMA website:
https://www.sandiegocounty.gov/content/dam/sdc/pds/SGMA/Prop-1-SDAC-Grant-Task-5-New-Extraction-Well-Site-Feasibility-Analysis.pdf

ID4-11

Water quality in ID4-11 is good and reasonably stable.

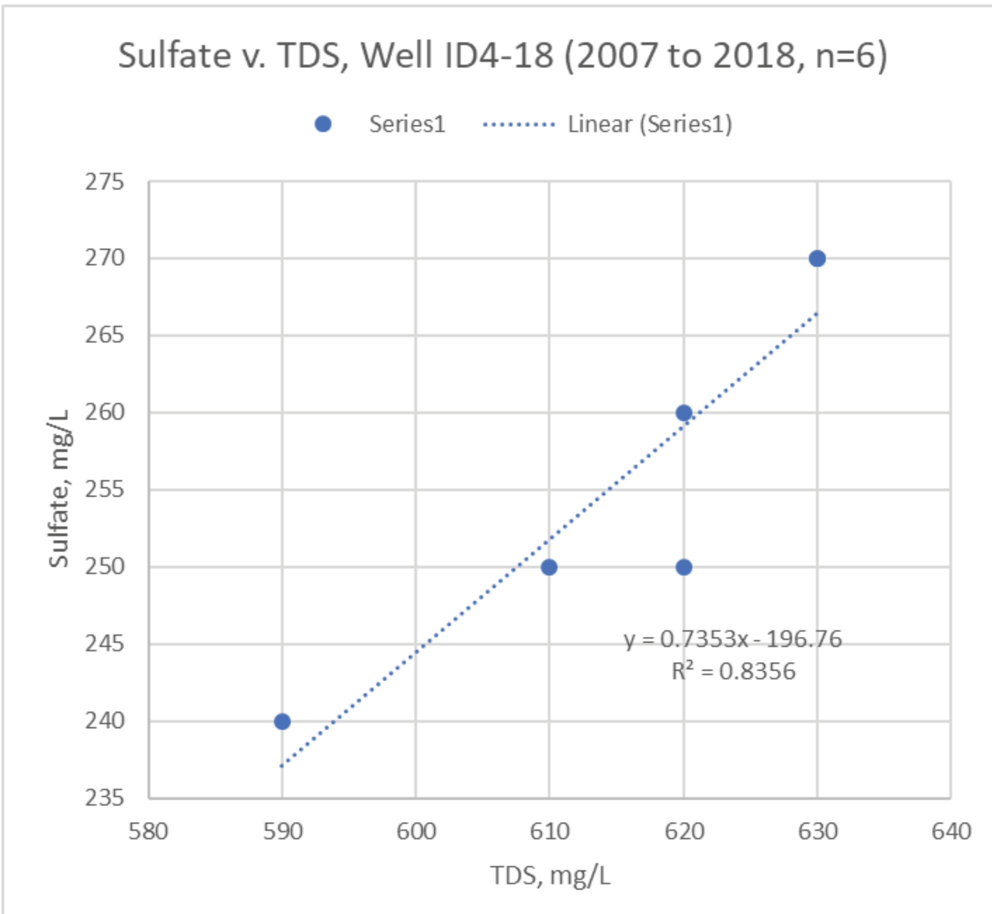
ID4-18

TDS is between the recommended and upper secondary MCL (currently at 630 mg/L). Sulfate is slowly increasing and is above the recommended secondary MCL of 250 mg/L. Arsenic has not been detected in this well (last reported as ND < 1.2 µg/L).

Figure 27 shows how TDS and sulfate are correlated and is presented as an example of how TDS measurements based on electrical conductivity testing may be able to be used to assess sulfate.

FIGURE 27

Date	TDS	Sulfate
5/8/2007	590	240
5/11/2010	620	260
6/10/2013	620	250
5/16/2016	610	250
11/17/2017	630	270
4/30/2018	630	270



4.2 Central Management Area (5: ID1-10, ID1-12, ID1-16, ID5-5, and Wilcox)

The Central Management Area is associated with both the "central" and "transitional" water quality type as indicated in **Figure 6** and COC-specific observations included in Table 4.

ID1-10
Water quality in ID1-10 is currently good and reasonably stable.

Elevated arsenic concentrations (a maximum of 12.2 μg/L that exceeded the MCL of 10 μg/L) were observed in 2014 that were preceded by elevated pHs of 8.2 to 8.4 (see **Figure 21**). Arsenic concentrations and elevated pH conditions have since declined.

ID1-12
Water quality in ID1-12 is currently good and reasonably stable.

ID1-16
Water quality in ID1-12 is currently good and reasonably stable.

Elevated arsenic concentrations (a maximum of 4.3 μg/L) were observed in 2014 that were preceded by and elevated pH of 8.3 (see **Figure 23**). Arsenic concentrations and elevated pH conditions have since declined.

ID5-5
Water quality in ID5-5 is currently good and reasonably stable.

Wilcox
Water quality in the Wilcox well is currently good and reasonably stable.

Elevated arsenic concentrations (a maximum of 7.8 μg/L) were observed in 2010 and 2014 that were preceded by elevated pH of greater than 8.6 (see **Figure 25**). Arsenic concentrations and elevated pH conditions have since declined.

4.3 South Management Area (1: ID1-8)

As previously discussed, the water chemistry observed in the South Management Area is distinctly different than that observed to the north. COC-specific observations are included in Table 4.

ID1-8

Water chemistry at ID1-8 has significantly changed over time, but now appears to be stabilizing. Water quality in ID1-8 is currently good.

Arsenic is of concern due to MCL exceedances consistently observed in nearby Ram's Hill wells.

Elevated arsenic concentrations (a maximum of 6.8 µg/L) were observed in 2010 that were preceded by an elevated pH of 8.3 (see **Figure 26**). Arsenic concentrations and elevated pH conditions have since declined.

5.0 SUMMARY

The multi-parameter assessment of water quality and COC trends provides additional insight compared to single parameter assessments.

Natural Water Chemistry (anions and cations)

- Natural water chemistry as determined by the eight dominant anions and cation systematically varies across the Subbasin (these include calcium [Ca], magnesium [Mg], sodium [Na], potassium [K], chloride [Cl], sulfate [SO_4], bicarbonate [HCO_3], and carbonate [CO_3]).

  The observed variations generally correlate with the previously established management areas that are further discussed in the GSP. Overall trends generally correlate with the well location relative to the pre-development groundwater flow paths and distance from where recharge waters enter the Subbasin,

- Water samples from BWD water supply wells show that the dominant cations and anions are sodium and calcium; and bicarbonate, sulfate, and chloride, respectively.

- The water type transitions from a calcium sulfate to a sodium chloride in the Northern Management Area wells.

- Sodium bicarbonate type water generally occurs in the South Management Area as tested. The groundwater analysis further supports that the South Management Area has distinctly different water quality than observed in the north and central groundwater management areas.

- The primary causes for the difference in water quality within the Subbasin include variations in the water being recharged (e.g. Coyote Creek versus San Felipe Creek), proximity of irrigated lands (e.g. nitrate impacts due to fertilizer application), aquifer lithology (local deposits of evaporites and potential arsenic-bearing clays), aquifer depth (related to increase in TDS), and location within the Subbasin with respect to the Borrego Sink where enhanced evaporation of ephemeral surface water occurs.

- Due to the location of the BWD wells this analysis does not fully represent the water quality distribution in the Subbasin. Refer to **Figures 4 and 7** for the well locations. As result the spatial trends identified among the wells are limited to examining variations along the western side of the Subbasin.

- Water quality as a function of depth has not been assessed in the BWD water supply wells, for example by the use of depth-specific water sampling. Well profiling data obtained by the DWR (**Figure 10**, for example) indicate that TDS linearly increases with depth. Given the high correlation with sulfate, the increase in TDS implies that sulfate will also increase with depth.

- Multiple aquifers are represented in the water chemistry data because of the construction of the 23 wells used in this report. As a result, water quality could not be differentiated in terms of the three-layer aquifer system (upper/middle/lower) used by the USGS and others (for example in the USGS Model Report).

- Temporal trends are more readily identified when multiple general mineral analyses are considered for each of the wells. Here Piper trilinear diagrams were used to assess the eight dominant anions and cations.

- 17 of the 23 wells had sufficient anion and cation data for temporal analysis and in some cases, well over 40 years data are available. Of these approximately 70 percent have experienced changes in water chemistry over time. The changes are generally attributed to long-term overdraft.

Chemicals of Concern (COCs)

- Five COCs were examined: arsenic, nitrate, TDS, sulfate, and fluoride. The overall analyses are improved when all five parameters are considered together and geochemical factors such as pH are included. The five COCs are depicted together with pH for each of the nine active BWD water supply wells in **Section 4**.

- Single parameter trend assessments, for example using Mann-Kendall trend analyses included in previous studies, are not repeated here.

- The COC analysis is based on a comparison of concentrations with current MCLs. Down-revision of the criteria, especially for arsenic, could have a large impact on BWD operations should water treatment be required. The State of California MCL for arsenic was last revised (from 50 to 10 ug/L) on 1/28/2008[25]. As of February 2017, there is no indication that the State Water Resources Control Board is planning to revise the arsenic MCL[26].

- Overall the water quality is currently good and water can be delivered without the need for advanced treatment. However, short-term water quality trends have been of concern, especially for arsenic. The following summarizes the analysis per COC.

[25] See: https://www.waterboards.ca.gov/drinking_water/certlic/drinkingwater/Arsenic.html

[26] Per a state review from 2017: "We are not aware of changes in treatment that would permit materially greater protection of public health, nor of new scientific evidence of a materially different public health risk than was previously determined. Thus, we do not plan on further review of the arsenic MCL." See: https://www.waterboards.ca.gov/drinking_water/certlic/drinkingwater/documents/reviewofmaximumcontaminantlevels-2017.pdf

Arsenic and Fluoride

Arsenic concentrations were increasing in multiple BWD water supply wells until 2014 and have since decreased. The potential for MCLS to be exceeded is of high concern to BWD due to the potential cost of water treatment and/or well replacement. The MCL was temporarily exceeded in one well, ID1-10. Review of the data shows that there is a relationship between pH and arsenic where elevated arsenic concentrations occur under alkaline conditions with pH levels of approximately 8 and greater. Especially noteworthy is that peak arsenic concentrations can be observed to occur after the peak pH was observed in multiple wells (ID1-10, ID1-16, Wilcox, and ID1-8). The lag time is approximately 2 to 4 years. While additional data and observations are required to further assess the connection between arsenic and pH, this relationship could prove important toward the monitoring and management of BWD's water supply.

Fluoride is discussed with arsenic because it has been observed to correlate with arsenic. While fluoride occurs at detectable concentrations in all of the active BWD wells, it has not been of concern as concentrations have typically been well less than 1.0 mg/L, less than half the MCL. Given the correlation it may prove useful towards future trend analyses for arsenic.

TDS and Sulfate

TDS represents the sum of all anions and cations that occur in the water. Here a number of these anions and cations have been observed to correlate with TDS. **Figures 15 through 17** show the correlation with TDS for sulfate, sodium, calcium, and chloride. A specific example is shown for well ID4-18 in **Figure 27** where TDS and sulfate are well correlated.

The USGS Model Report (p. 2) identified TDS and sulfate as "the only constituents that show increasing concentrations with simultaneous declines in groundwater levels".

Electrical conductivity measurements are commonly used to assess TDS. In this case they can be used as a field-based monitoring tool for TDS, and in turn support tracking of sulfate. The TDS profiles presented by DWR (**Figure 10**) are examples of electrical conductivity measurements used to evaluate TDS.

Nitrate

Historically there have been significant nitrate-related water quality problems encountered in BWD wells that led to well reconstruction, abandonment, and replacement. These wells were typically producing water from the uppermost portion of the aquifer system. As noted in **Table 4**, nitrate occurs in all of the active BWD wells at varying concentrations well below the MCL. Nitrate predominantly occurs as a result of fertilizers contained in irrigation return flow, and from septic systems. Historically, because the upper portion of the aquifer system is unconfined, nitrate has primarily affected wells that were completed (open to flow) at the water table.

The USGS Model Report (p.2) noted that "TDS and nitrate concentrations were generally highest in the upper aquifer and in the northern part of the Borrego Valley where agricultural activities are primarily concentrated".

Nitrate concentrations are primarily related to land-based activities and do not correlate with inorganic water quality data. Overall determination of historical impacts and ongoing susceptibility of the aquifer to nitrate contamination will require review of prior, current, and future land use placed in a spatial context. Work done by DWR (for example as illustrated in **Figure 11**) is an example of how land use information can be used. Among the land use parameters that would go into a nitrate source analysis would the location and types of septic and sewer systems, current and historical agricultural activities, and current and historical irrigated turf/golf courses.

5.1 Other Potential COCs

This report focused on the dominant anions and cations, and the five primary COCs. Other potential COCs include naturally-occurring uranium and radionuclides. Anthropogenic COCs include herbicides, pesticides, and similar chemicals used for agriculture and turf management. Microbial contamination, typically associated with animal wastes and sewage/septic, is also of potential concern.

Groundwater quality provided by BWD water supply wells is currently good and meets California drinking water maximum contaminant levels (MCLs). To date the current wells are producing water without the need for treatment. The BWD public water supply monitoring program is conducted in compliance with the State of California's requirements as administered by the State Water Resources Control Board Division of Drinking Water (DDW) and includes a wide range of analytes.

BWD provides all sampling data to the DDW, and is listed as public water supply CA3710036. A summary of BWD's sampling program for other COCs can be reviewed in the annual consumer confidence report, available online at http://nebula.wsimg.com/c30a61991a5160ddf5e577fe9f7b3c01?AccessKeyId=D2148395D6E5BC38D600&disposition=0&alloworigin=1. The BWD is also sampling all of its water supply well semi-annually as part of the GSA monitoring network rather than the minimum 3-year timeframe currently required by DDW.

5.2 Recommendations

- The COC analysis supports expansion of groundwater monitoring and testing program to include field-based water quality measurements of water being produced by BWD. Monthly wellhead measurements are recommended for electrical conductivity (EC), pH, and oxidation-reduction (redox) potential. These could be conducted at the same time BWD personnel collect monthly bacteria samples. EC can be used to calculate TDS, and by correlation estimate sulfate in some wells. Redox and pH are key geochemical parameters that can readily be measured at the wellhead by BWD personnel.

- Conduct vertical profiling and depth-specific sampling of water supply wells when the wells become accessible, for example during pump removal for maintenance. The primary goals of the testing are to identify potential zones where water quality may be poor and to examine the relative rate of flow of water into the well with depth. Both types of information will support assessment of well performance as overdraft continues.

  Long-term the vertical profiling will provide data to better understand the water quality trends and support BWD water management planning. For example, the data will support assessment of sulfate trends by understanding how concentrations may or may not be increasing with depth and support projections of how water quality will change as overdraft while pumping reductions occur over the 20-year GSP planning period.

- Use the groundwater model to assess pre- and post-SGMA groundwater flow conditions and potential changes in water chemistry. Current pumping conditions have changed groundwater flow patterns within the North and Central Management Area due to the establishment of two pumping centers. Future pumping reductions will likely alter groundwater flow patterns. The model can be used to support calculations of groundwater flow rates and directions using ‘particle tracking’, a methodology that looks at how water flows over time. The modeling software (USGS Modflow model) includes Modpath, a post-processing software that works with the model output.

- Use the groundwater model water balance to develop a ‘mixing cell’ calculation of salt balance to assess the potential rate of accumulation of dissolved minerals associated with water use. The Subbasin is effectively a closed system where dissolved minerals and other solutes have will continue to accumulate over time. The primary purpose of the calculations is to assess long-term TDS changes that result from irrigation and septic return flows as overdraft continues. The calculations will also support examination of areas where BWD water production may need to be established using new or existing water wells.

- Investigate the potential causes of the temporary increases in arsenic concentrations and pH observed in BWD wells as a means of predicting future arsenic concentrations. A lag time of 2 to 4 years is observed in multiple BWD wells where elevated pH preceded the increase in arsenic concentrations that could prove to be important towards BWD's water supply and risk management.

- Expand on the analysis of nitrate in groundwater relative to land use as described by the DWR (e.g. **Figure 11**). Additional discussion of the occurrence of nitrate in groundwater is included in the GSP that describes land uses within the Subbasin.

- Expand the water chemistry and water quality evaluation to areas within and downgradient of the agricultural areas in the North and Central Management Areas.

- Continue to collect the full suite of general minerals (8 anions and cations) together with pH and redox measurements. Water chemistry parameters should be collected using 'flow cells' where the chemistry of the water is tested before it is exposed to the atmosphere.[27]

- Conduct selective sampling for phosphate and review the overall electrochemical balance for all potential anions and cations to determine why the current data have excess cations relative anions (see **Section 3.2.1**).

- Further assess lithologic and geochemical conditions associated with the occurrence of arsenic. For example, work done in the San Joaquin valley (discussed in **Section 3.6.1**) linked the release of water from clay to increased arsenic concentrations in groundwater. Further review of Subbasin stratigraphy work done by Netto (2001) is warranted. Re-analysis of the geostatistical work done by the USGS to evaluate sediment lithologies may also prove useful towards understanding the nature and extent of sediments potentially associated with arsenic. Lithologic sampling and

[27] An example is shown below. Water flows directly from the well into a chamber where measurements are made. From: http://www.geotechenv.com/flowcell_sampling_systems.html. It is understood that Dudek staff are using flow cells during sampling of Rams Hill wells to measure pH, specific conductance, temperature, turbidity, dissolved oxygen, oxygen-reduction potential, and color. Their Sampling and Analysis Plan could be used for the remaining wells within the GSP monitoring program.

Geotech Flowblock
<40 mL cell volume for flow rates of
100 mL/min to 1 gpm (3.8 LPM)

geochemical testing for arsenic and related minerals is recommended during the installation of new wells.

- Investigate the potential interaction of microbially-mediated oxidation and reduction processes (e.g. denitrification and sulfate reduction) specific to arsenic mobility.

- Examine the potential application of recharge basins to facilitate arsenic removal as a result of geochemical processes in the vadose zone (see discussions in Section **3.6.1**).

- Develop an inventory of abandoned wells, including well completion information and potential condition. Abandoned wells have the potential to act as conduits for the downward flow of shallow groundwater contaminants such as surface applied fertilizers, agricultural chemicals, and turf management chemicals. Abandoned wells may need to be properly destroyed per California Well Standards (See information available from the County of San Diego https://www.sandiegocounty.gov/content/sdc/deh/lwqd/lu_water_wells.html)

- Continue to track changes in groundwater quality as a function of water level to assess trends relative to the potential for water quality degradation and the likelihood of the need for water treatment. Use the data to assess potential cost and water system reliability risks to BWD.

- Continue to track water treatment technologies and costs for arsenic as the potential for revision of the arsenic MCL is, in part, dependent on cost-benefit analyses for water treatment (see COC discussion in Section 5).

6.0 REFERENCES

All references are cited within the text using footnotes.

APPENDIX A

DWR, 2014

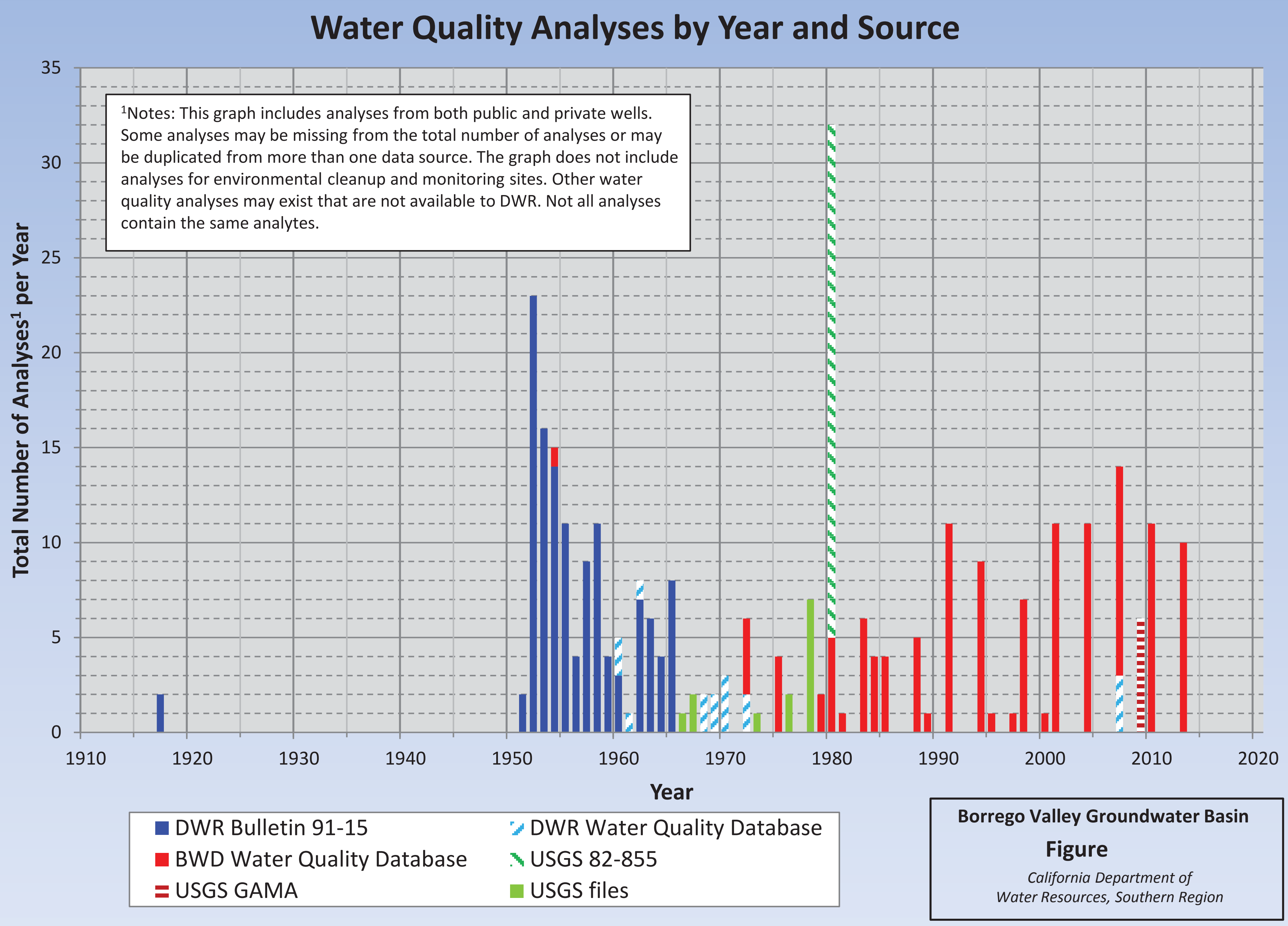
Groundwater Quality Information
for
Borrego Valley

DEPARTMENT OF WATER RESOURCES
STATE OF CALIFORNIA

Groundwater Quality Information for Borrego Valley

DEPARTMENT OF WATER RESOURCES
STATE OF CALIFORNIA

Southern Region May 2014



More than 300 water quality analyses have been identified.

Borrego Valley Groundwater Quality

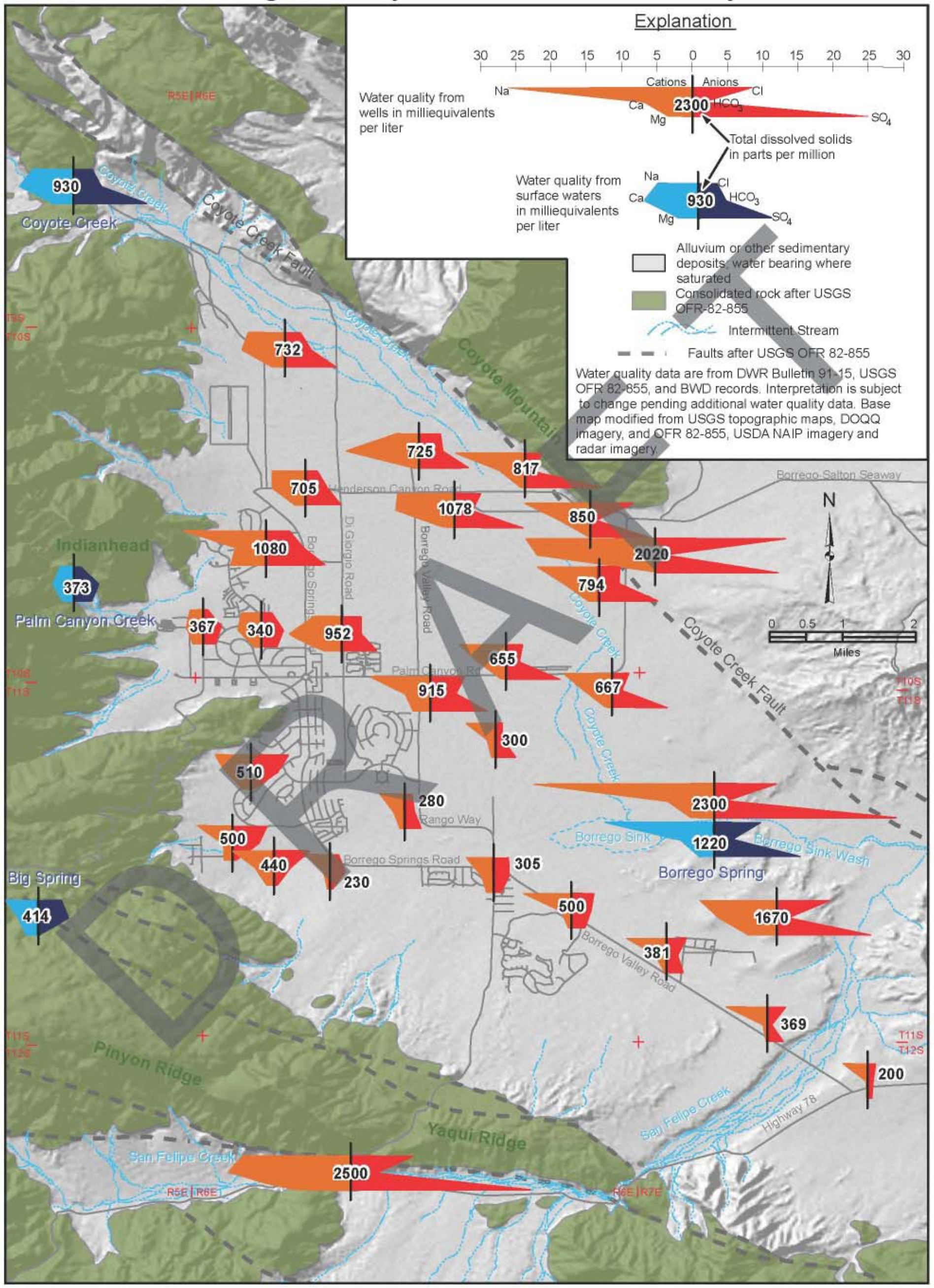


Figure showing major water quality constituents in groundwater and surface water in Borrego Valley. The high proportion of Sulfate in the surface water of Coyote Creek appears to dominate the character of groundwater in the northern and eastern parts of the basin. The more Bicarbonate waters of Borrego Palm Canyon and Big Spring influence the groundwater along the western and southern parts of the basin.

Borrego Valley Water Quality Analyses of Nitrates

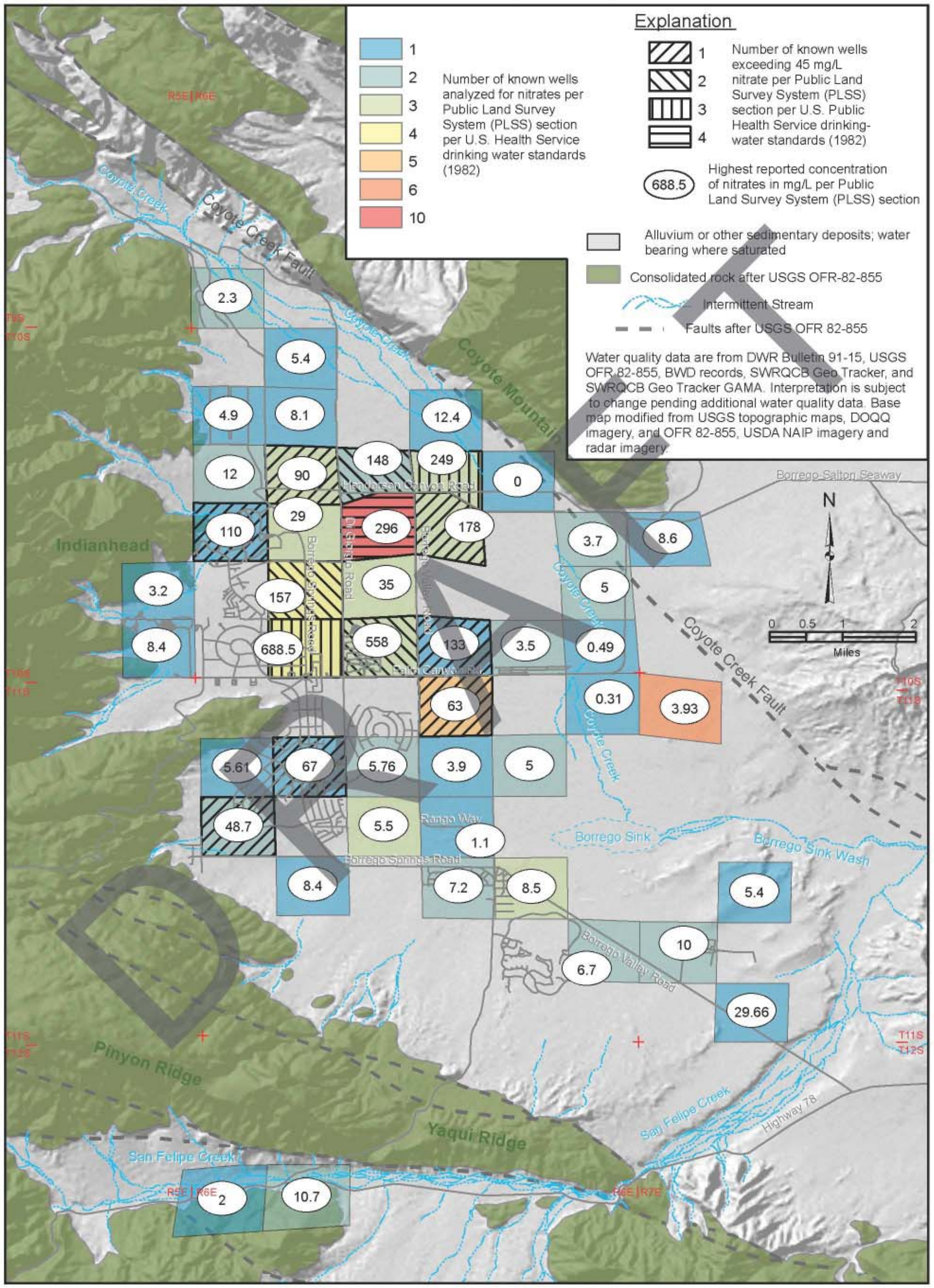
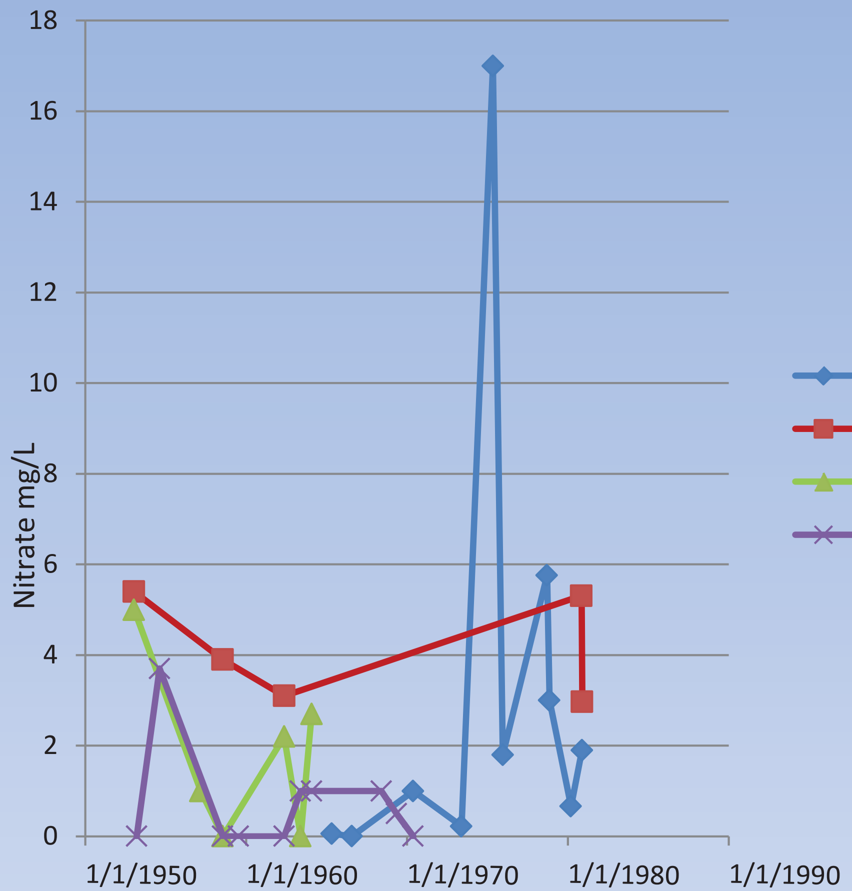
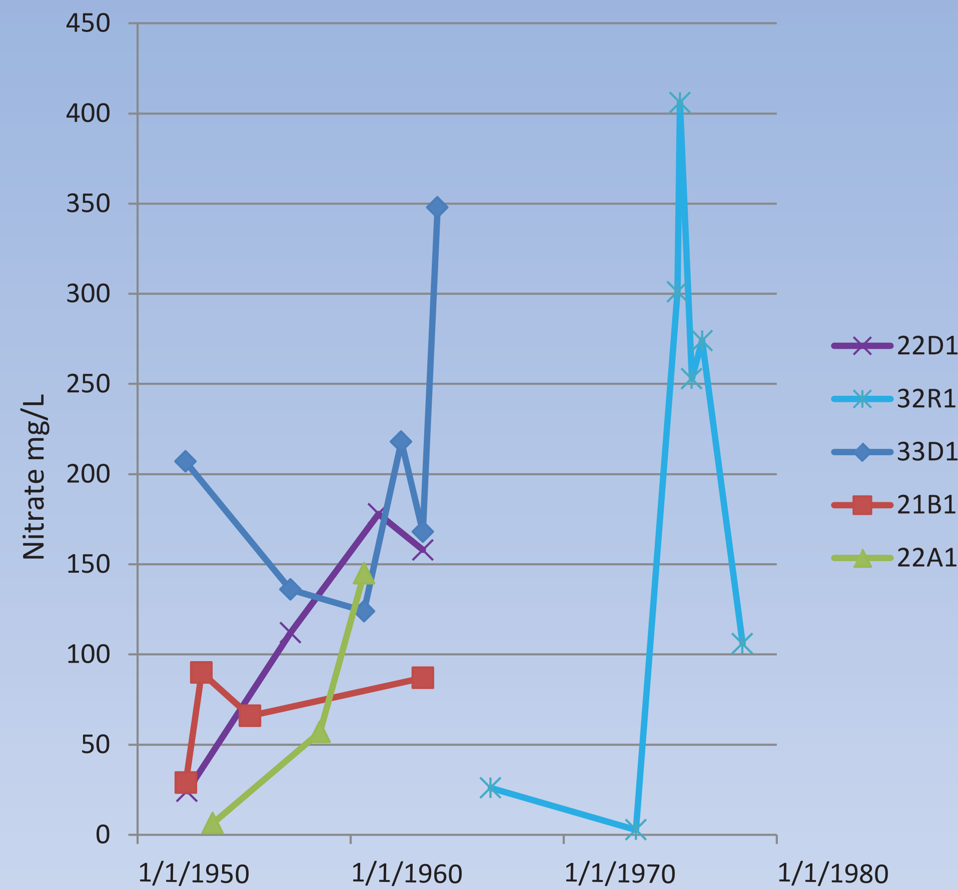


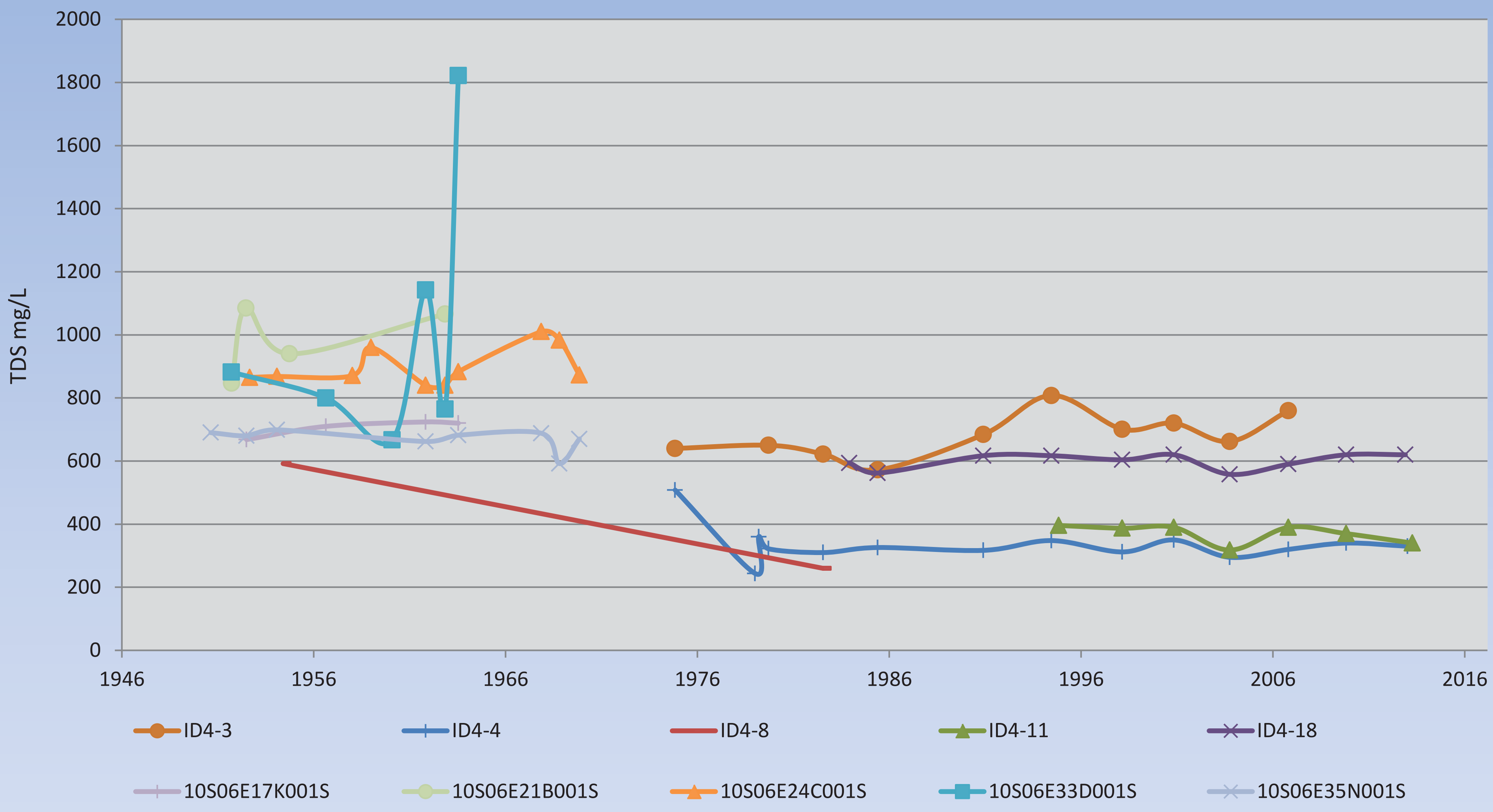
Figure showing the distribution of Nitrate analyses for the Borrego Basin. Maximum content is shown per section and sections are colored according to the number of analyses in the section. Sections where the maximum contaminant level (MCL) are exceeded are shown in hatched patterns.





Nitrate content is graphed through time for several wells in the Borrego Basin.
No obvious trend is apparent. (MCL is 45 mg/L)

North Borrego Valley



Graph showing change in TDS content through time for several wells in the northern part of the basin. No clear increase in TDS is observed.

South Borrego Valley

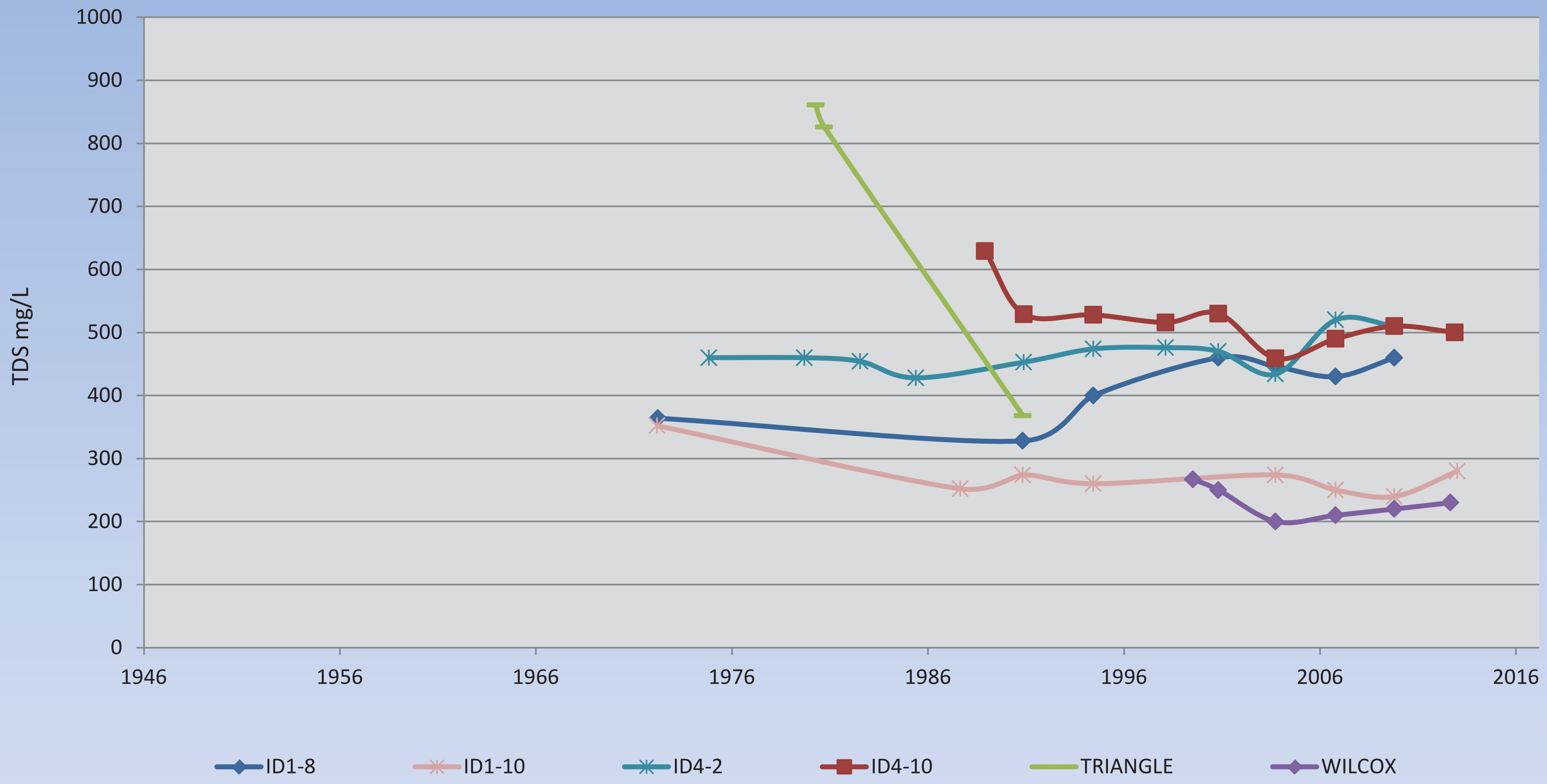
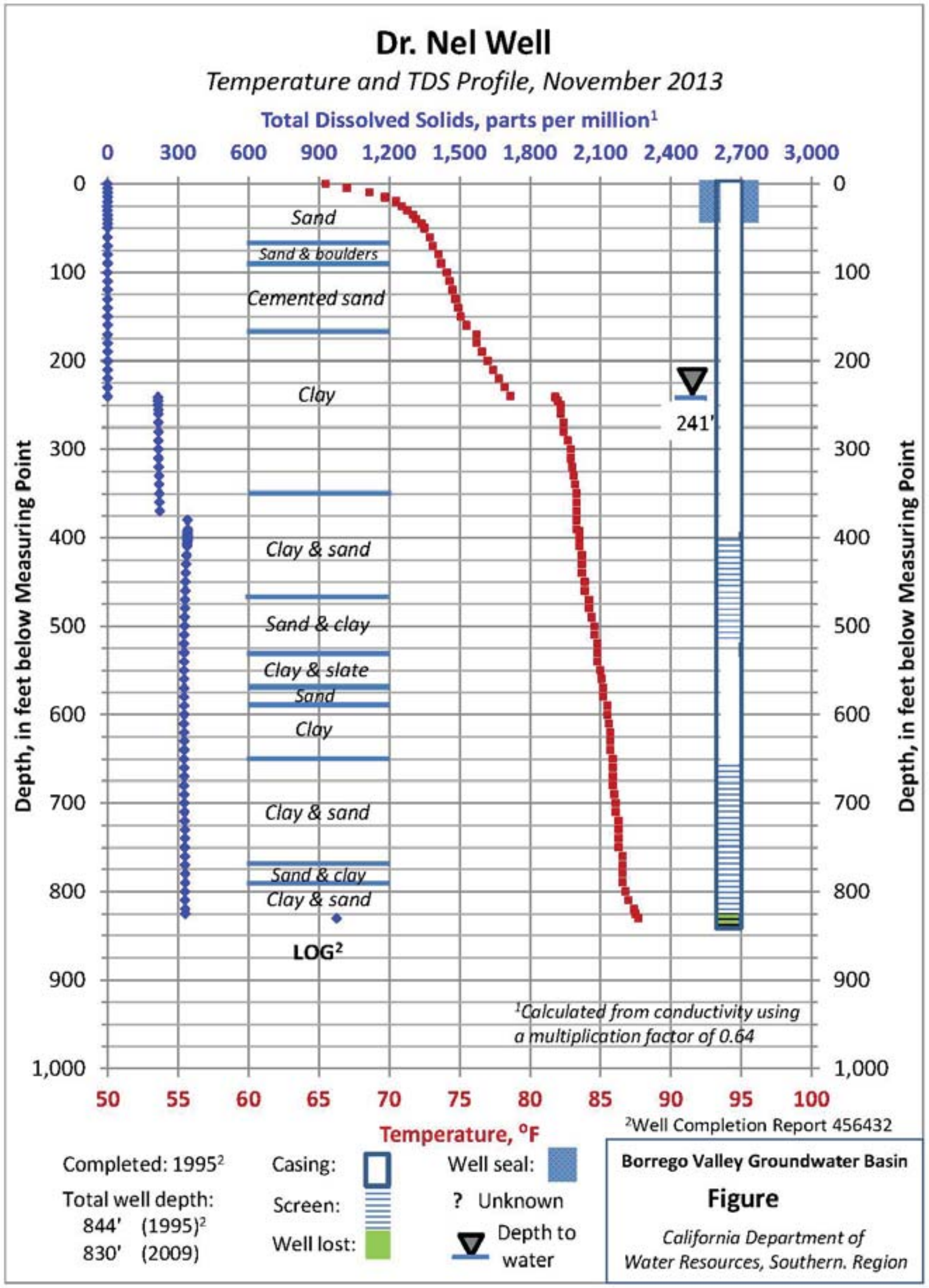
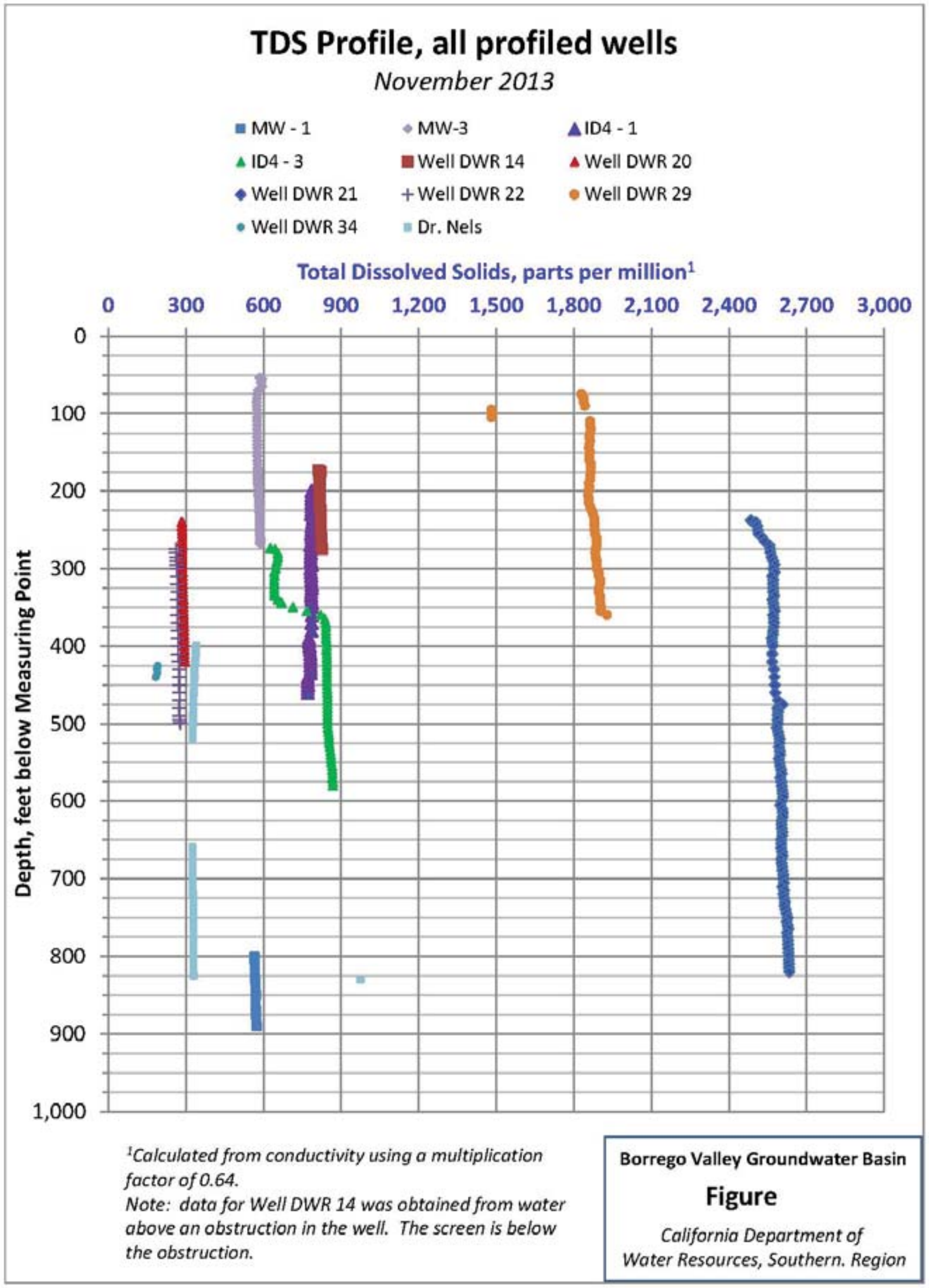


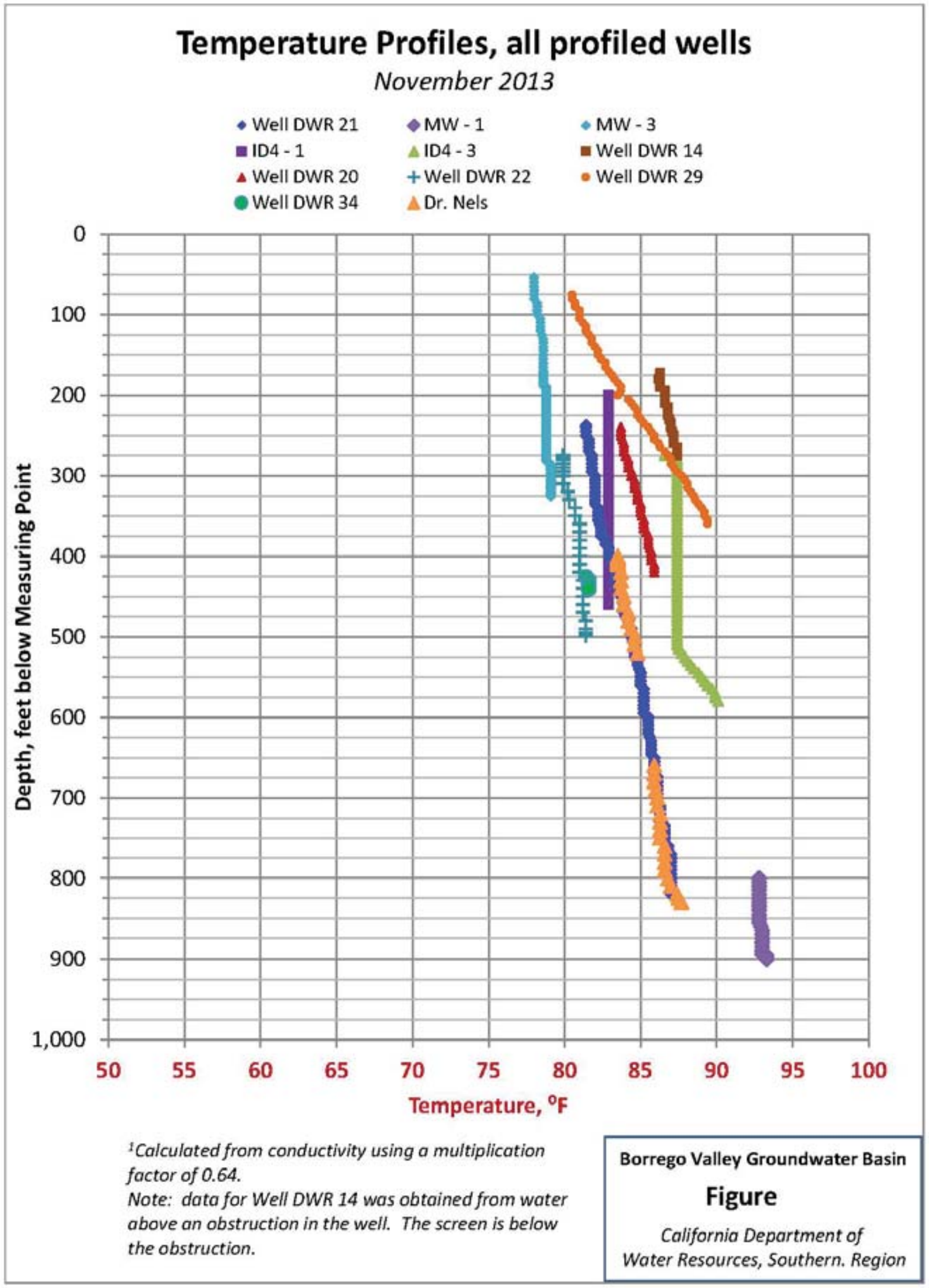
Figure showing TDS content through time for several wells in the southern portion of the basin. Most show decrease in TDS through time.



A profile of TDS content and temperature for Dr. Nel's Well. Changes in TDS appear to occur at the well screen. TDS does not change appreciably with depth through the screened interval. Temperature rises steadily with depth.



Profiles of TDS with respect to depth for wells in Borrego Valley. Most show slight increase in TDS with depth



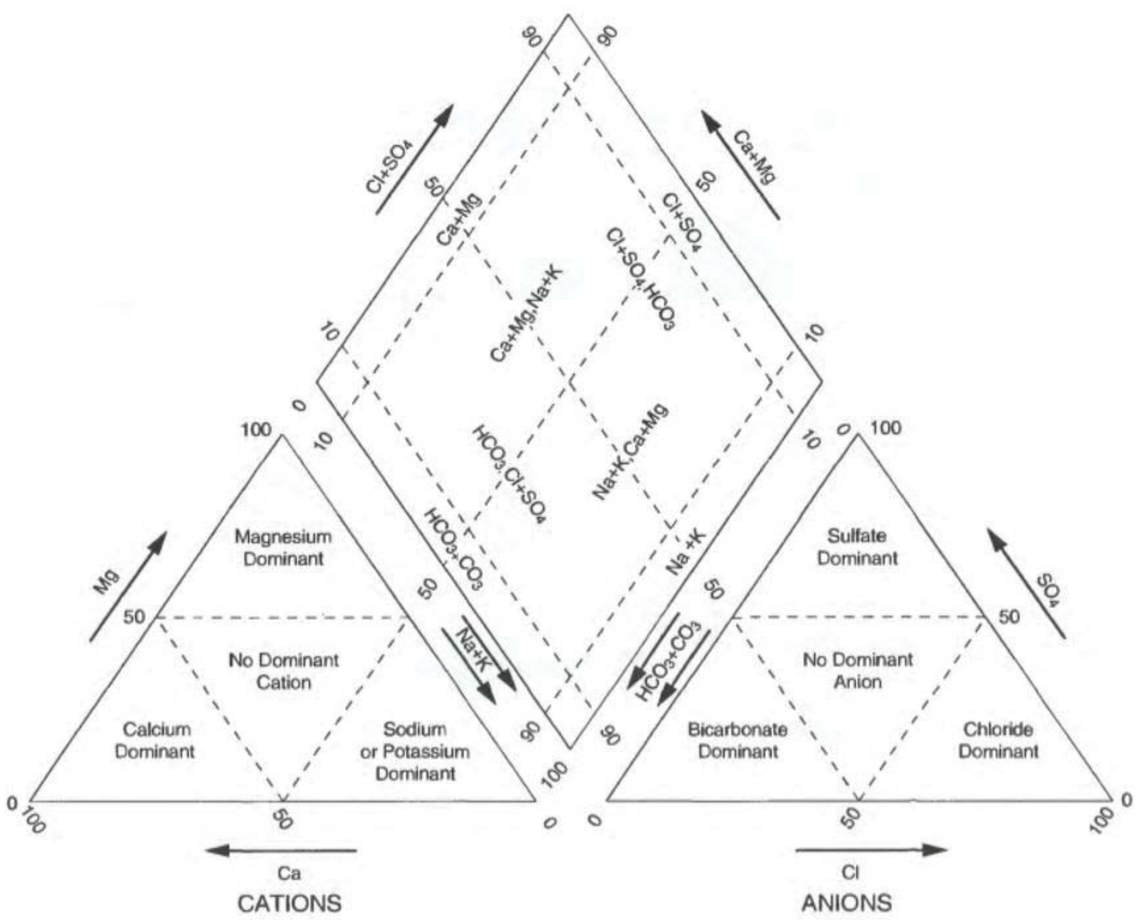
Profiles of Temperature with respect to depth. Most wells show increase in temperature with depth.

Summary

- More than 300 analyses identified
- Water character reflects recharge source
- More than 100 Nitrate analyses, widespread
- No apparent trend through time for Nitrate or TDS
- 11 Wells profiled for Temperature and TDS
- No consistent trend for TDS with depth in well.

APPENDIX B

PIPER DIAGRAMS, ALL WELLS

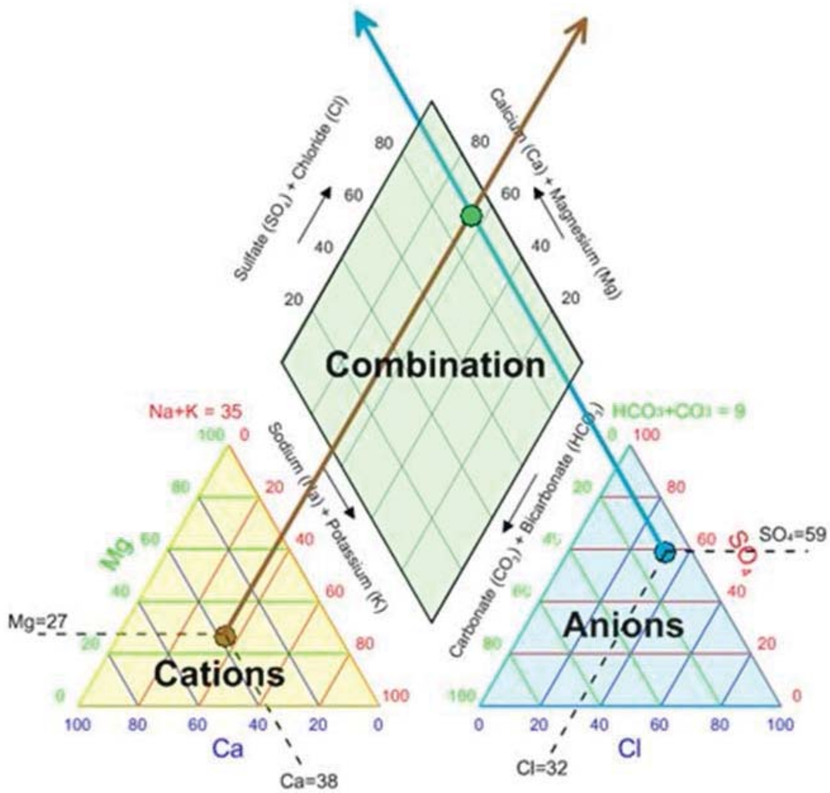


A. Classification scheme for hydrochemical facies.

APPENDIX B: PIPER DIAGRAMS

B.1 EXPLANATION OF PIPER DIAGRAMS

The eight dominant anions and cations that occur in groundwater can be used to describe of the type of water. A Piper trilinear diagram[1] combines sodium and potassium (cations), and carbonate and bicarbonate (anions) to reduce the total number of anions and cations from eight to six, with 3 values for each. This allows the anions and cations to be depicted using ternary diagrams. The values are then then projected onto a central diamond. An example of the projection follows:



From: https://support.goldensoftware.com/hc/en-us/articles/115003101648-What-is-a-piper-plot-trilinear-diagram-

The values used for the anions and cations are converted from mass/liter to milliequivalents/liter, a measure of the relative number of anions and cations in the solution. For example, if NaCl is dissolved into pure water there are an equal number of sodium cations (Na^+) and chloride anions (Cl^-). An analysis by weight will show that there is more chloride because chloride has a larger molecular weight (MW) - the MW of Na is 22.9 grams/mole versus Cl that has a MW of 35.45 grams/mole. 'Equivalents' are derived by dividing the reported mass by the MW so that the relative number of ions (in moles) is calculated.

[1] Piper, A.M. 1944. A graphic procedure in the geochemical interpretation of water-analyses. Transactions-American Geophysical Union 25, no. 6: 914–923

APPENDIX B: PIPER DIAGRAMS

The overall intent of the diagram is to support grouping and classification of water types, also termed hydrochemical facies. An example follows from https://www.hatarilabs.com/ih-en/what-is-a-piper-diagram-and-how-to-create-one

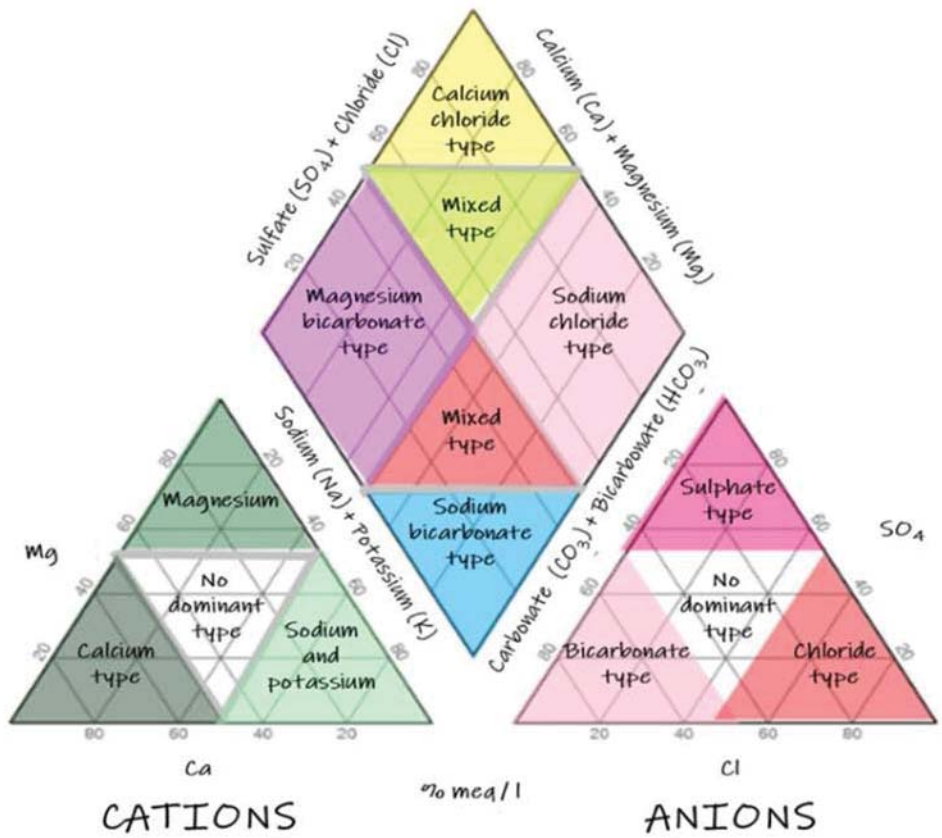


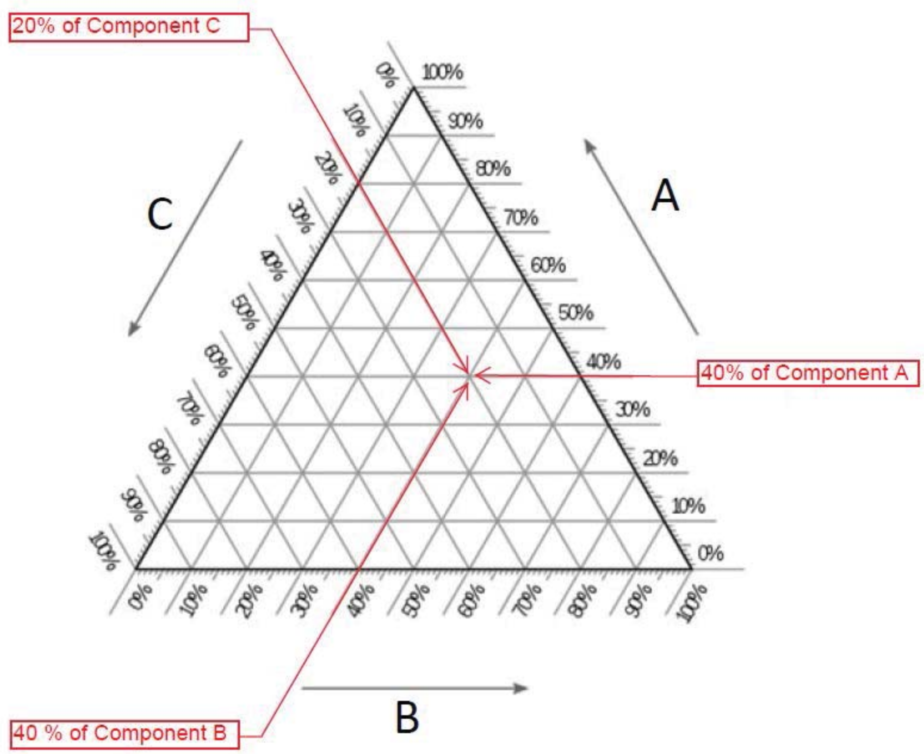
FIGURE 1A: HYDROCHEMICAL FACIES IN THE CATION AND ANION TRIANGLES AND IN THE DIAMOND.

The lower triangles are ternary diagrams that represent the relative proportion of anions or cations. The various types of water, or facies, are shown in the middle diamond.

Piper diagrams depicted in this report use a colored field scheme implemented in the Python programming language as published by Peeters, 2014[2]. Rather than drawing an underlying grid, the colored fields are used to help the visual interpretation of the data. The computations and graphics were developed using open source program code published by Peeters.

[2] Peeters, L., 2014. A Background Color Scheme for Piper Plots to Spatially Visualize Hydrochemical Patterns. Vol. 52, No. 1–Groundwater–January-February 2014

The following is an example of the ternary grid and how data are plotted:



All values equal 100% on the triangular grid. The highest percentage of each of the components occurs in the extreme corners of the triangle.

Values increase as indicated by the arrows.

Source:
https://upload.wikimedia.org/wikipedia/commons/thumb/a/ac/Blank_ternary_plot.svg/486px-Blank_ternary_plot.svg.png

APPENDIX B.2 PIPER DIAGRAMS USED IN THE REPORT

The following diagram are presented in the following order:

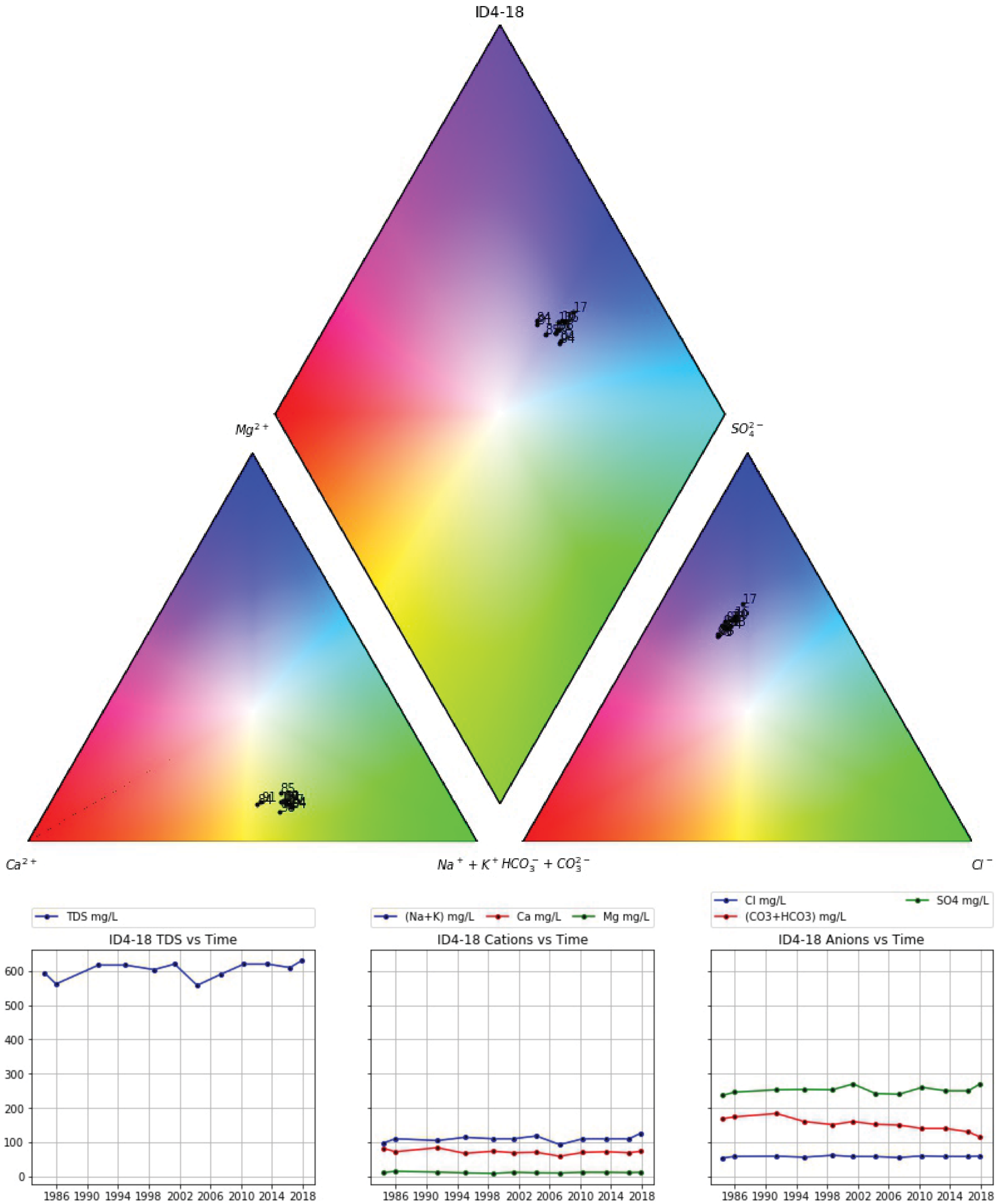
1: ID4-7 (not included due to insufficient data)
2: ID4-18
3: ID4-3
4: ID4-4
5: ID4-11
6: Cocopah
7: ID4-5
7A: ID4-1
8: ID5-5
9: ID1-12
10: ID4-2
11: ID4-10
12: ID1-16
13: Wilcox
14: ID1-10
15: ID1-8
16: RH-3
17: RH-4
18: RH-5
19: RH-6
20: ID1-1
21: ID1-2
22: Jack Crosby
23: WWTP (insufficient data)
24: MW-3 (insufficient data)

Recent Data: All (Piper only)
Recent Data: North and Central (Piper only)
Recent Data: South (Piper only)

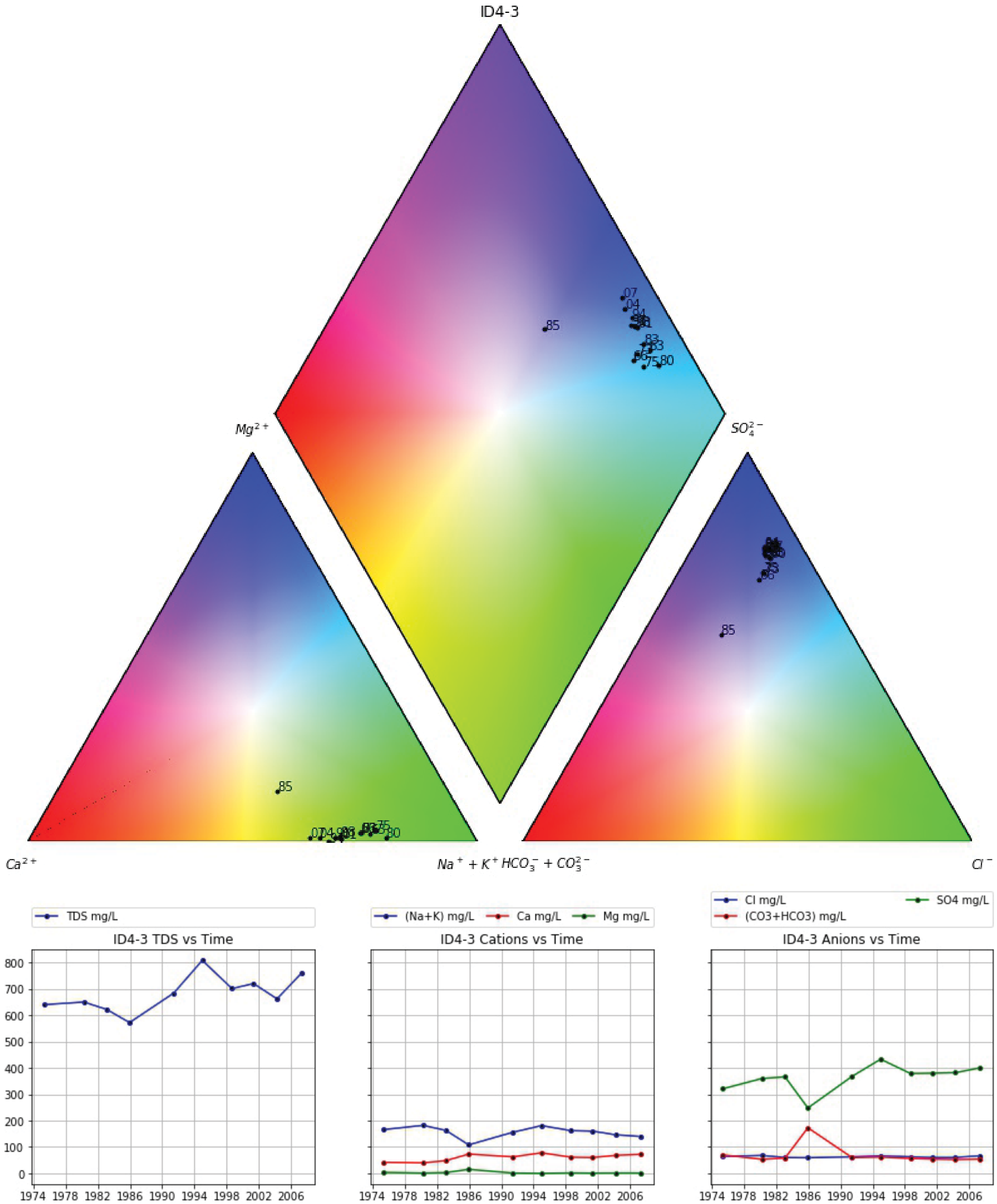
A copy of the map follows (**Figure 4**, from main body of report)

APPENDIX B: PIPER DIAGRAMS

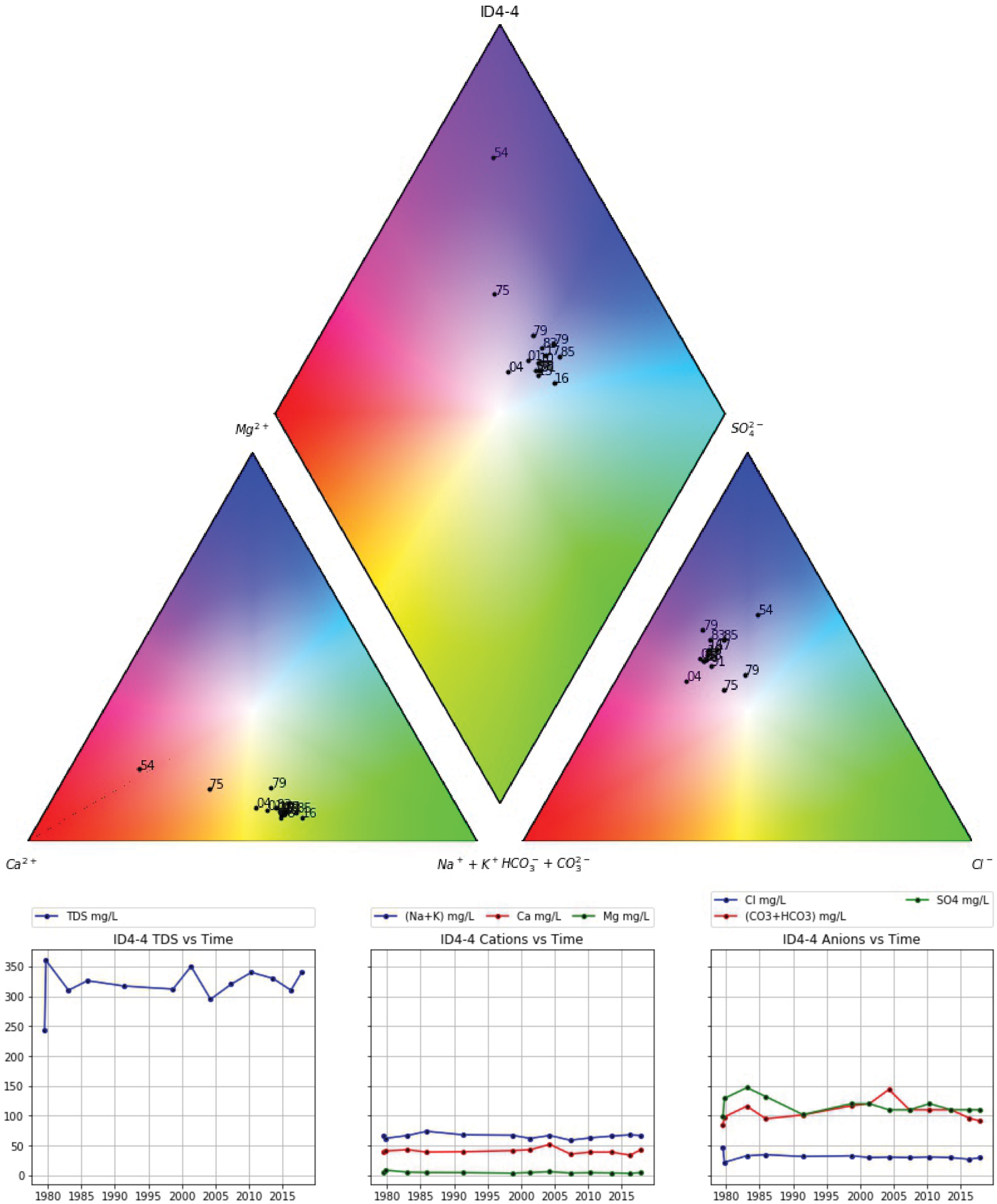
2: ID4-18


ID4-18
Mg^{2+}
SO_4^{2-}
Ca^{2+}
$Na^+ + K^+$ $HCO_3^- + CO_3^{2-}$
Cl^-
TDS mg/L
ID4-18 TDS vs Time
(Na+K) mg/L
Ca mg/L
Mg mg/L
ID4-18 Cations vs Time
Cl mg/L
SO4 mg/L
(CO3+HCO3) mg/L
ID4-18 Anions vs Time

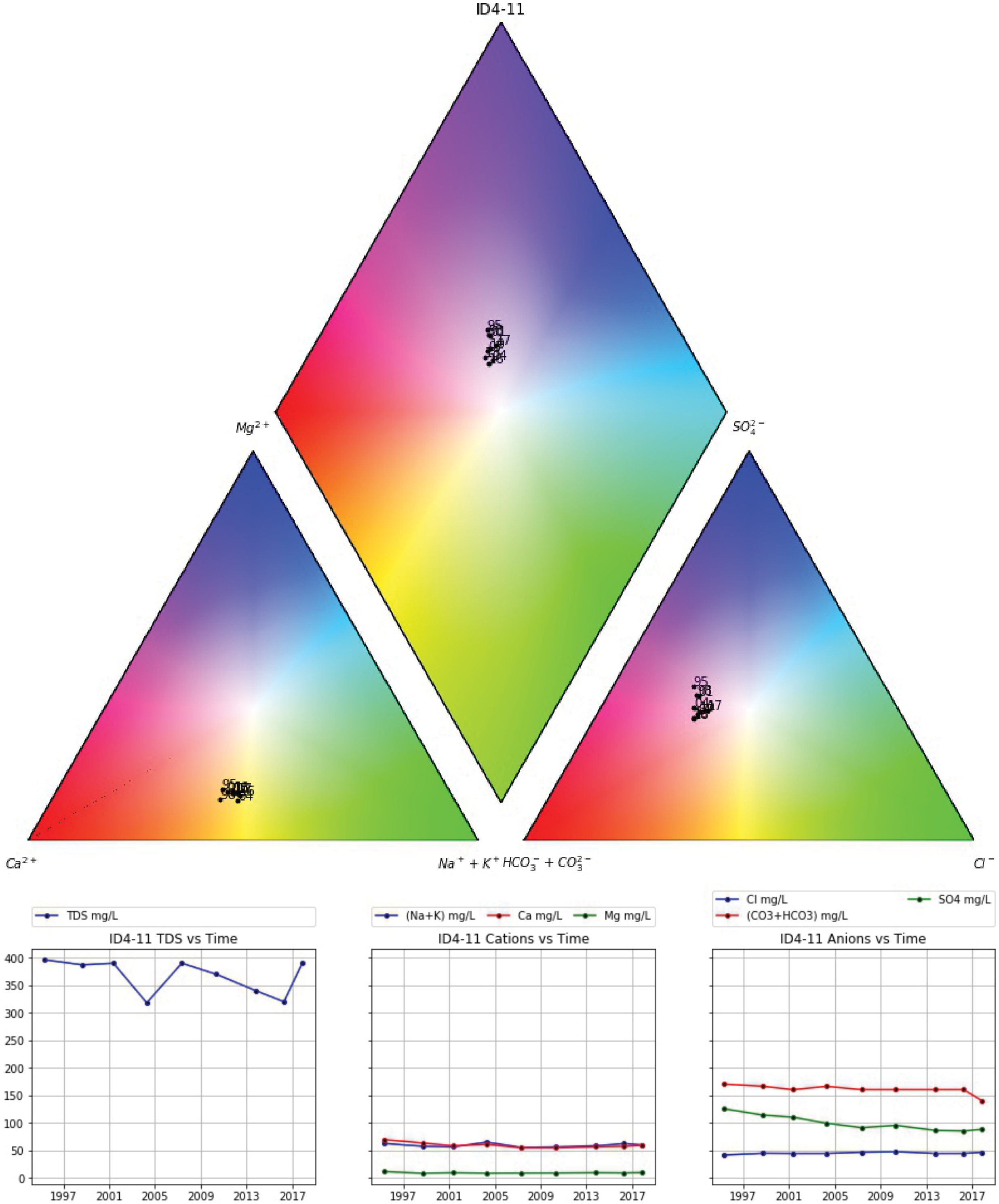
3: ID4-3


ID4-3
Mg^{2+}
SO_4^{2-}
Ca^{2+}
$Na^+ + K^+$ $HCO_3^- + CO_3^{2-}$
Cl^-
TDS mg/L
ID4-3 TDS vs Time
(Na+K) mg/L
Ca mg/L
Mg mg/L
ID4-3 Cations vs Time
Cl mg/L
(CO3+HCO3) mg/L
SO4 mg/L
ID4-3 Anions vs Time

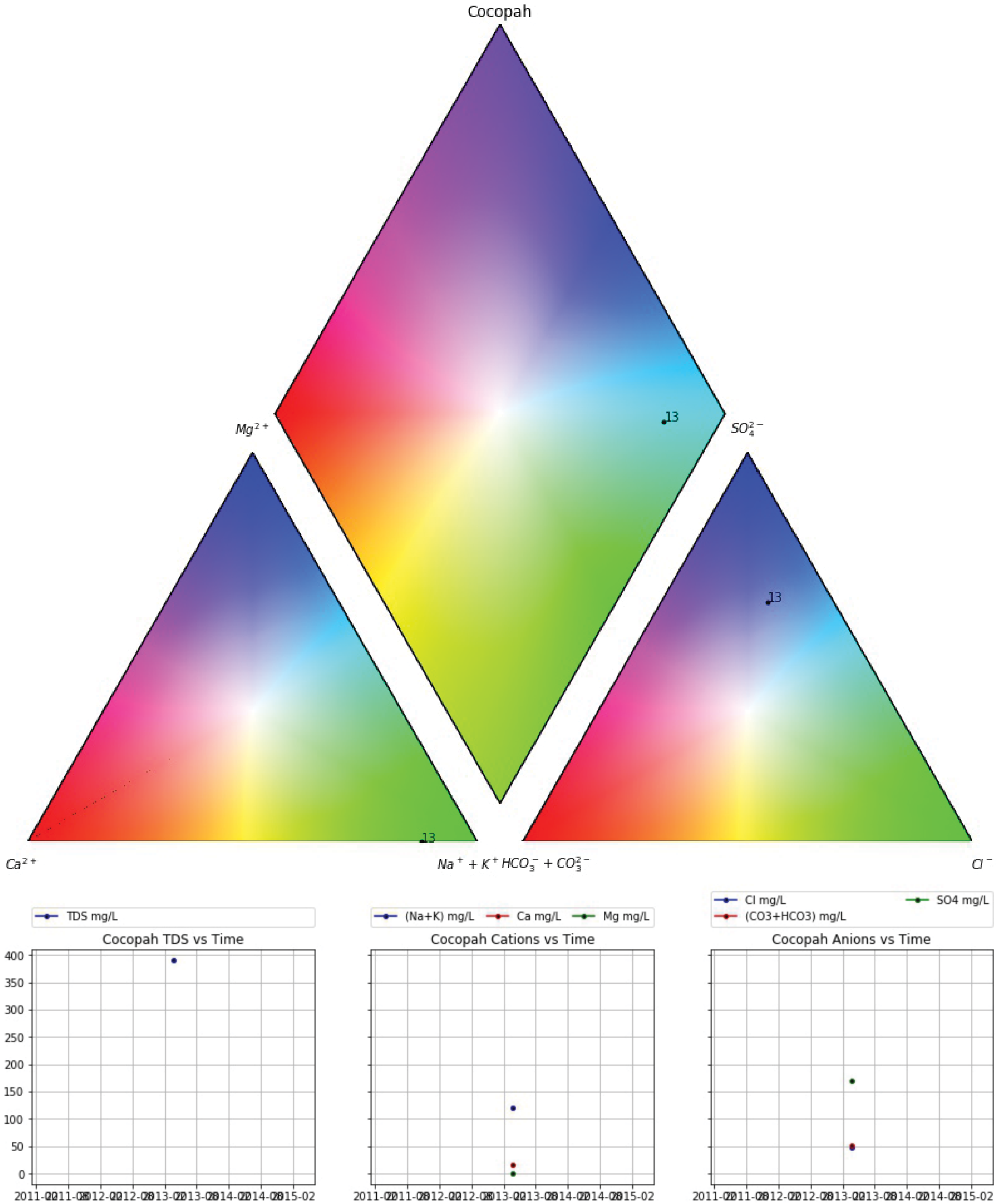
4: ID4-4


ID4-4
Mg2+
SO42−
Ca2+
Na+ + K+ HCO3− + CO32−
Cl−
TDS mg/L
ID4-4 TDS vs Time
(Na+K) mg/L
Ca mg/L
Mg mg/L
ID4-4 Cations vs Time
Cl mg/L
SO4 mg/L
(CO3+HCO3) mg/L
ID4-4 Anions vs Time

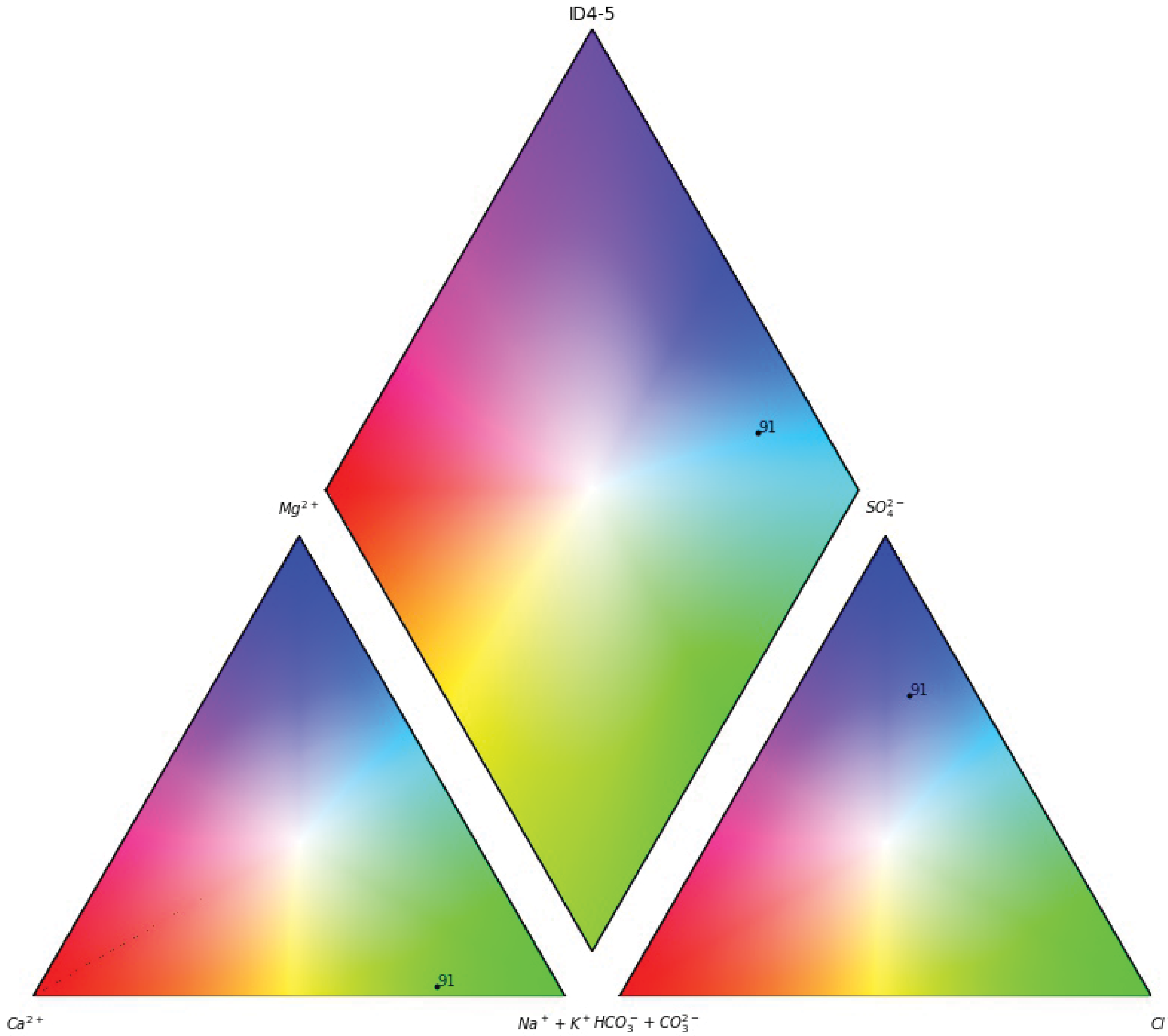
5: ID4-11

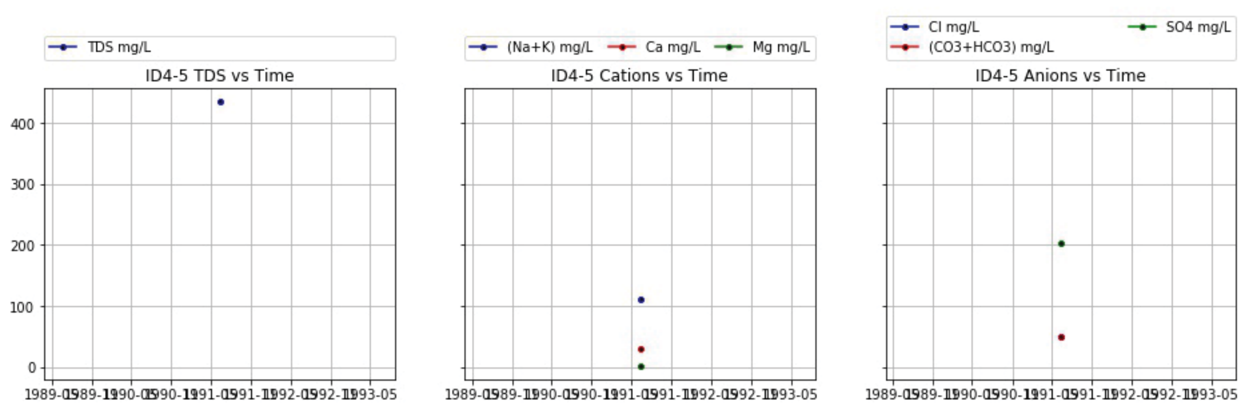

ID4-11
Mg2+
SO42−
Ca2+
Na+ + K+ HCO3− + CO32−
Cl−
TDS mg/L
ID4-11 TDS vs Time
(Na+K) mg/L
Ca mg/L
Mg mg/L
ID4-11 Cations vs Time
Cl mg/L
SO4 mg/L
(CO3+HCO3) mg/L
ID4-11 Anions vs Time
1997
2001
2005
2009
2013
2017

6: Cocopah

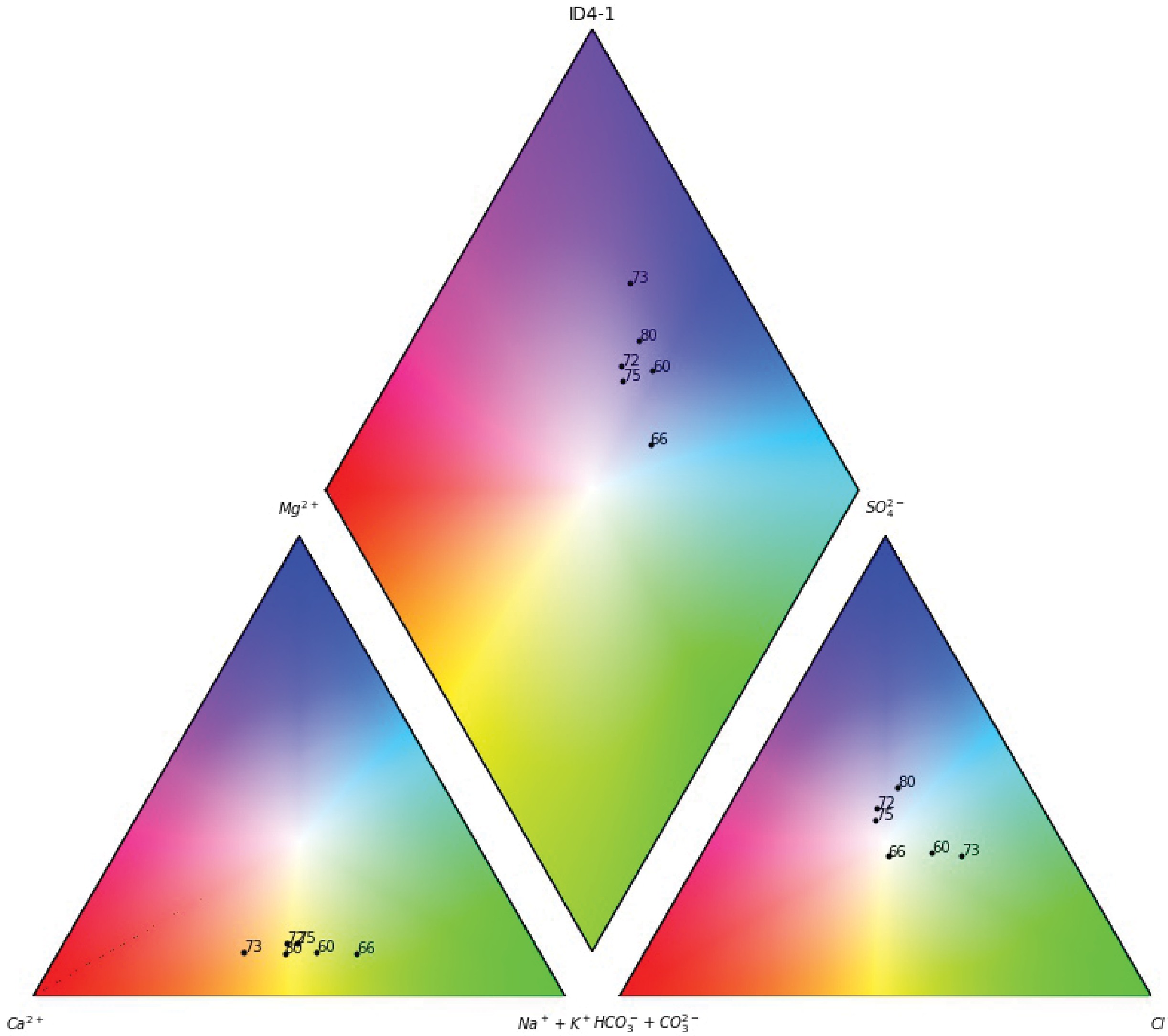

Cocopah
13
13
13
Mg^{2+}
SO_4^{2-}
Ca^{2+}
$Na^+ + K^+$ $HCO_3^- + CO_3^{2-}$
Cl^-
TDS mg/L
Cocopah TDS vs Time
(Na+K) mg/L
Ca mg/L
Mg mg/L
Cocopah Cations vs Time
Cl mg/L
SO4 mg/L
(CO3+HCO3) mg/L
Cocopah Anions vs Time

7: ID4-5

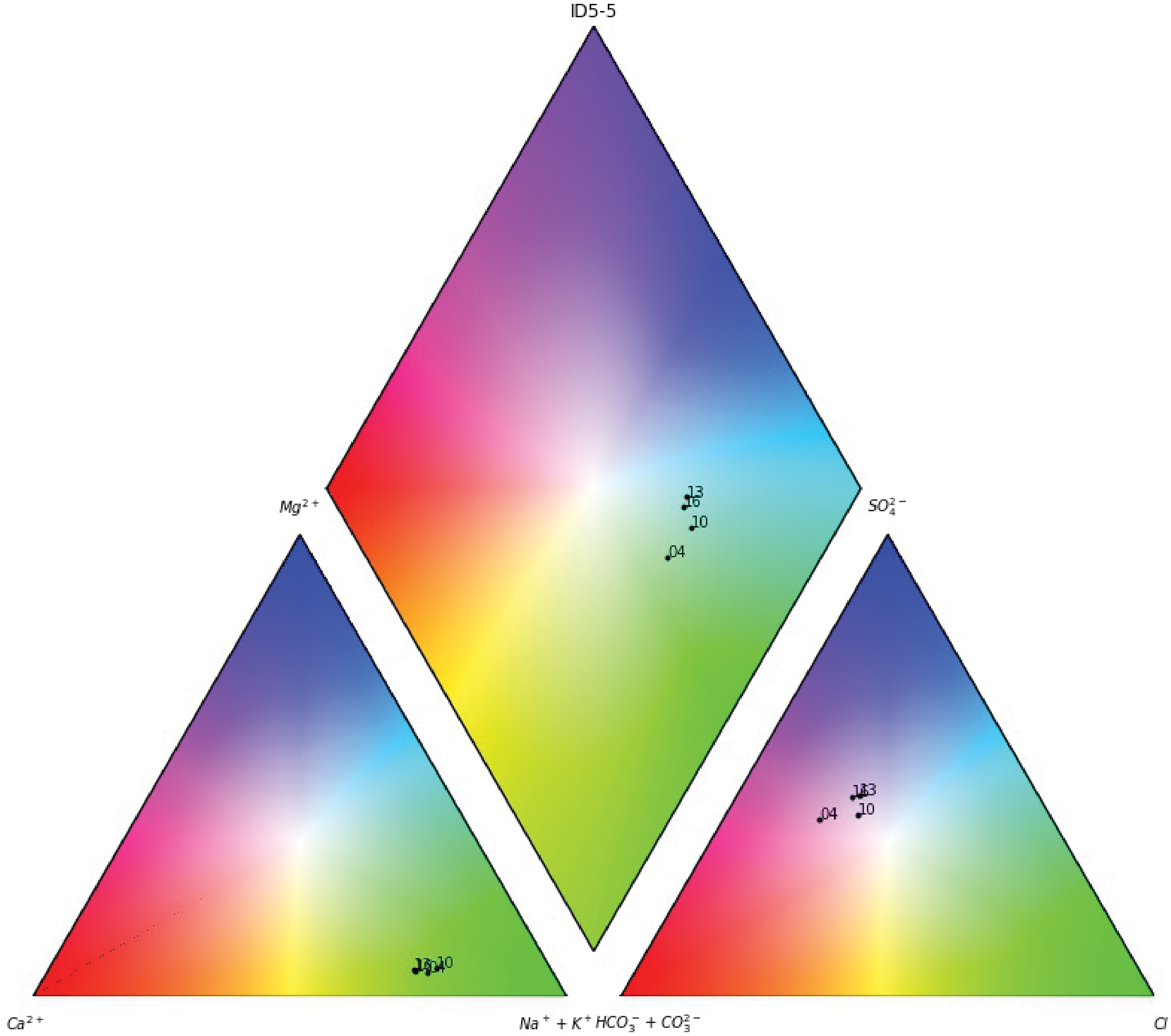

ID4-5
91
Mg2+
SO4 2-
Ca2+
Na+ + K+ HCO3- + CO3 2-
Cl-

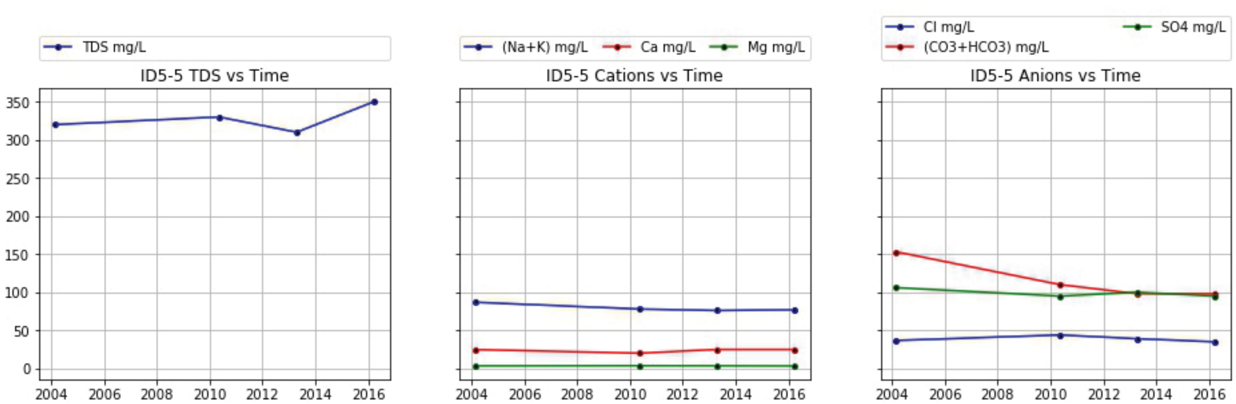

TDS mg/L
ID4-5 TDS vs Time
(Na+K) mg/L
Ca mg/L
Mg mg/L
ID4-5 Cations vs Time
Cl mg/L
SO4 mg/L
(CO3+HCO3) mg/L
ID4-5 Anions vs Time
0
100
200
300
400
1989-05
1993-05

7A: ID4-1

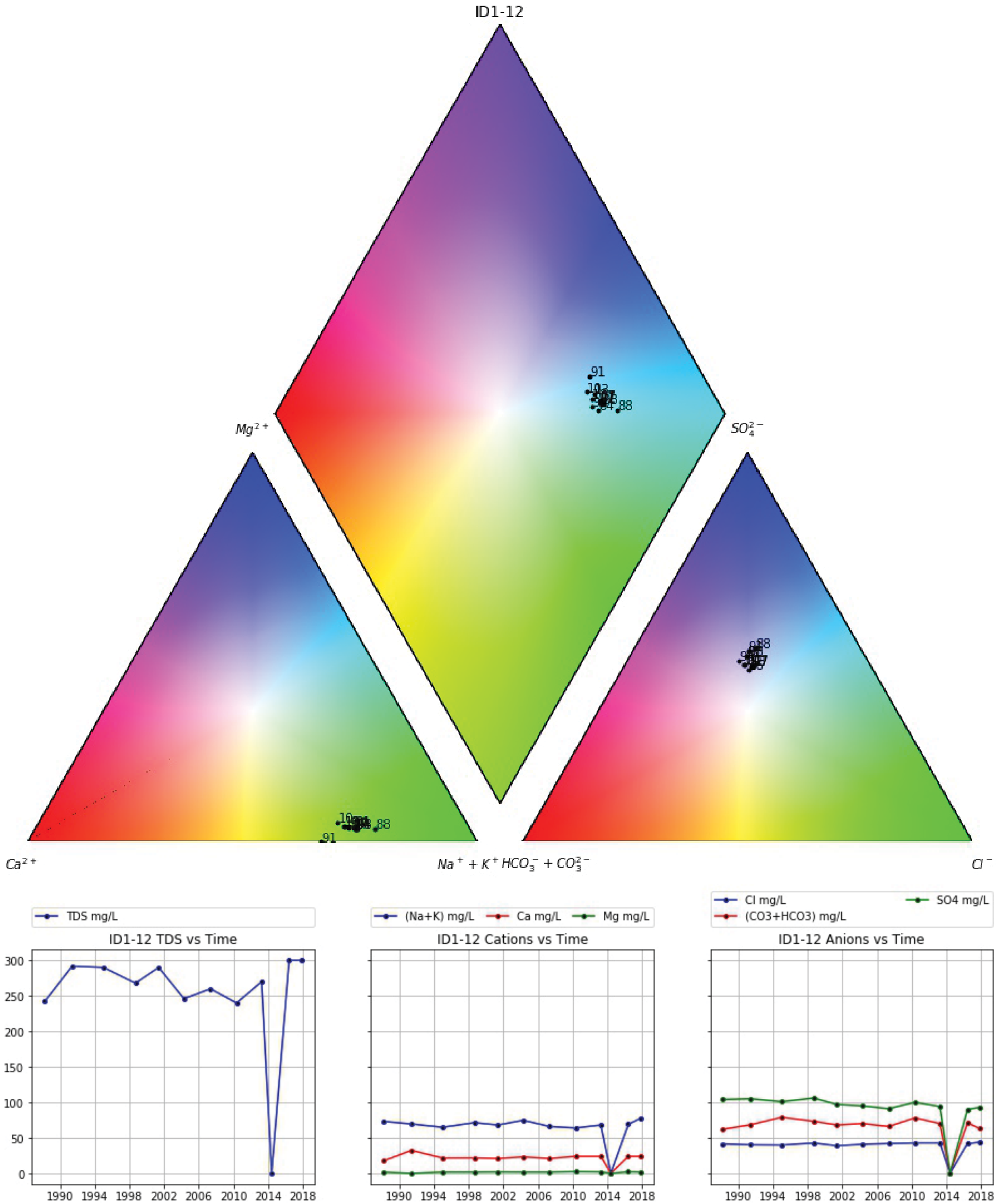


8: ID5-5

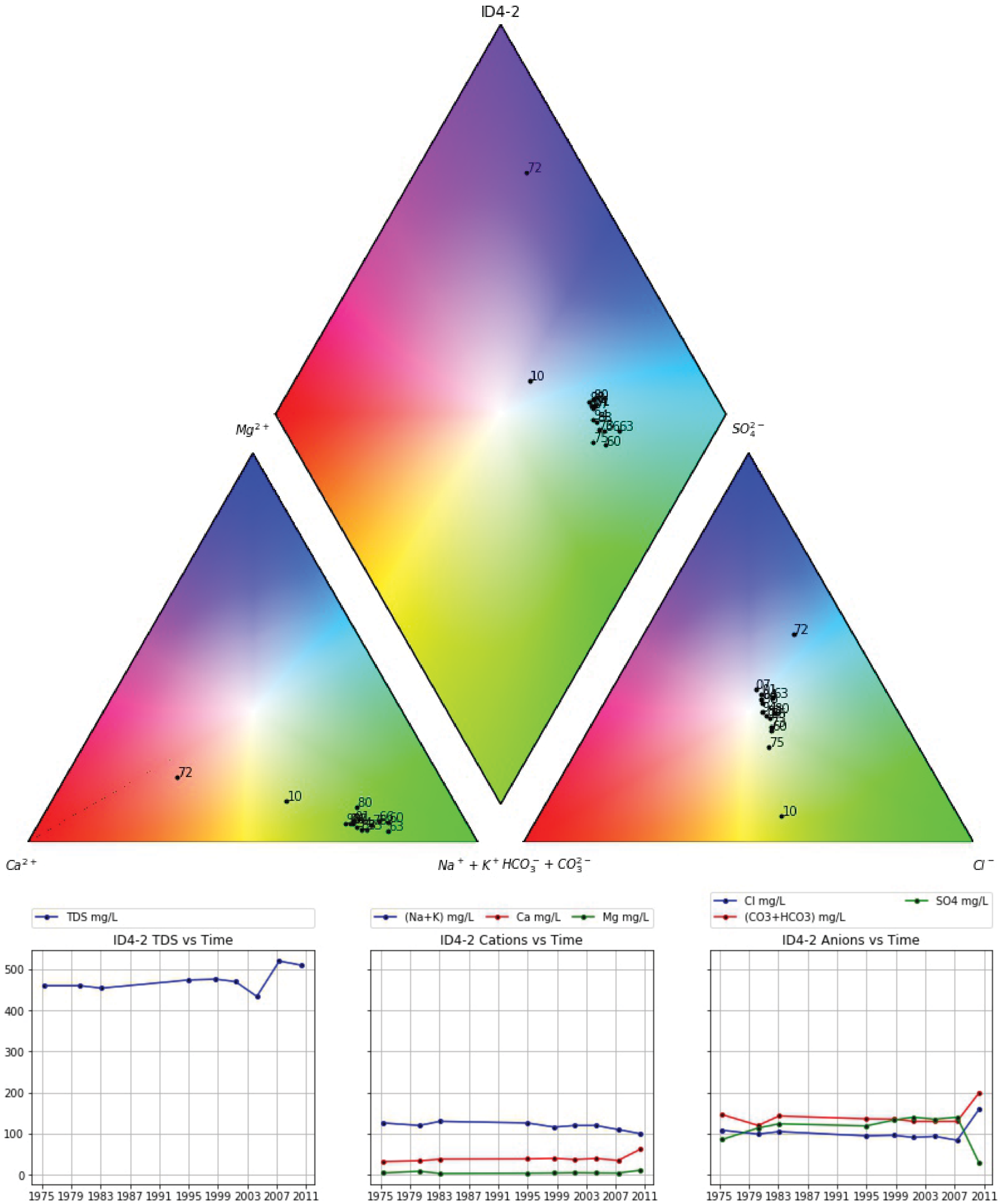

ID5-5
Mg^{2+}
SO_4^{2-}
13
16
10
04
13
16
13
10
04
10
Ca^{2+}
$Na^+ + K^+$ $HCO_3^- + CO_3^{2-}$
Cl^-


TDS mg/L
ID5-5 TDS vs Time
350
300
250
200
150
100
50
0
2004
2006
2008
2010
2012
2014
2016
(Na+K) mg/L
Ca mg/L
Mg mg/L
ID5-5 Cations vs Time
Cl mg/L
SO4 mg/L
(CO3+HCO3) mg/L
ID5-5 Anions vs Time

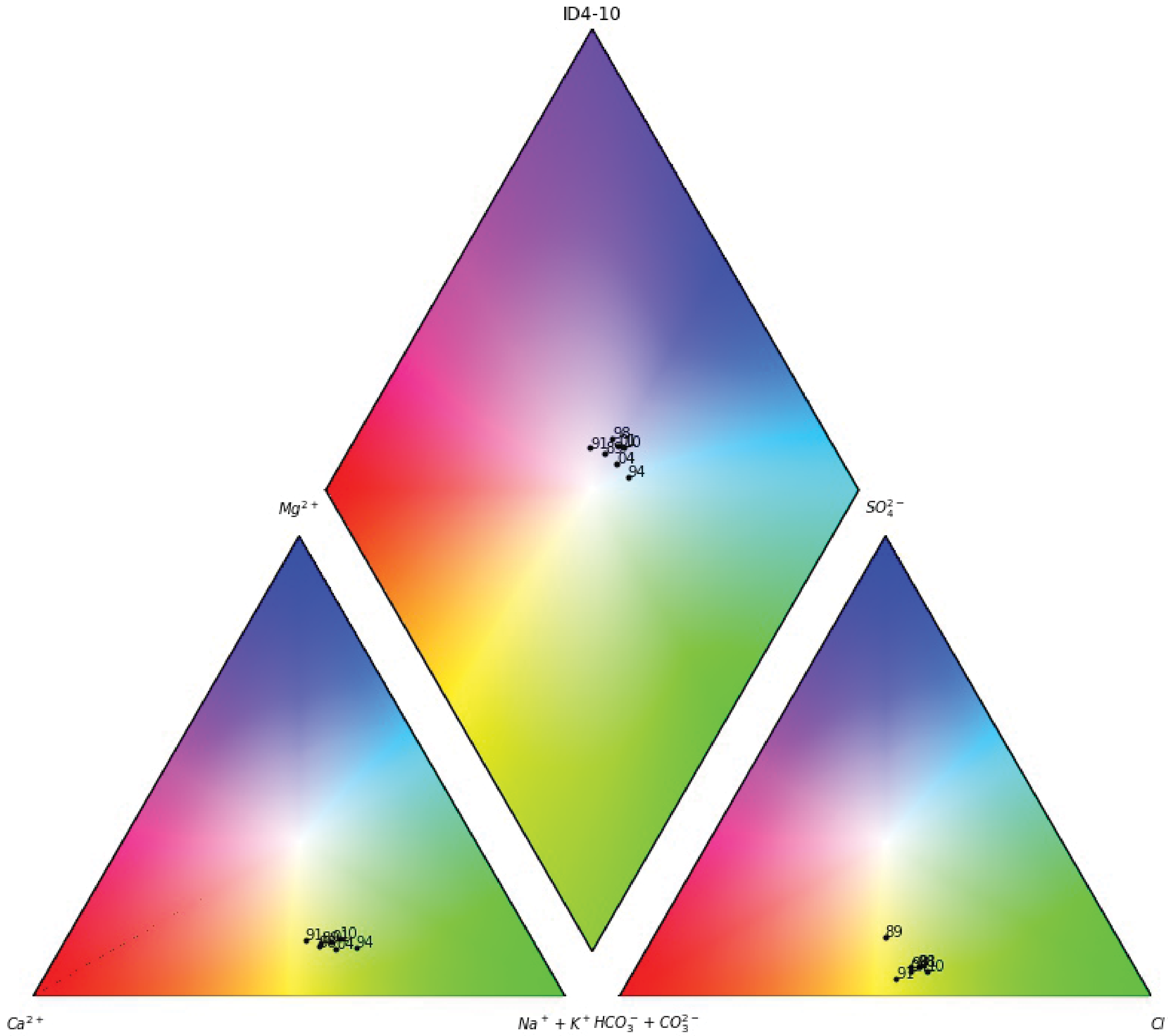
9: ID1-12

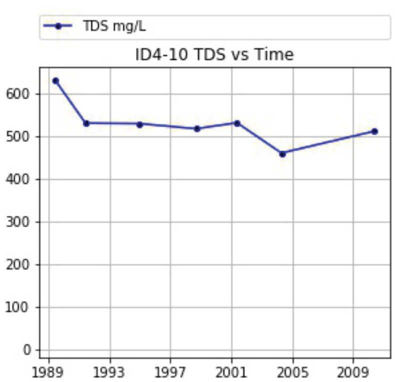

ID1-12
Mg^{2+}
SO_4^{2-}
Ca^{2+}
$Na^+ + K^+$ $HCO_3^- + CO_3^{2-}$
Cl^-
91
88
TDS mg/L
ID1-12 TDS vs Time
(Na+K) mg/L
Ca mg/L
Mg mg/L
ID1-12 Cations vs Time
Cl mg/L
(CO3+HCO3) mg/L
SO4 mg/L
ID1-12 Anions vs Time
0
50
100
150
200
250
300
1990
1994
1998
2002
2006
2010
2014
2018

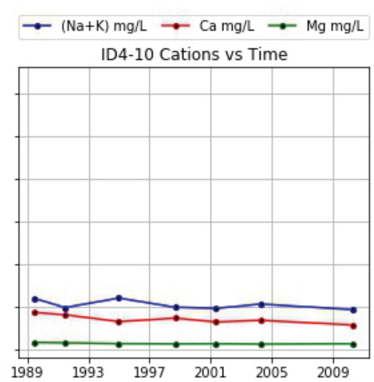
10: ID4-2

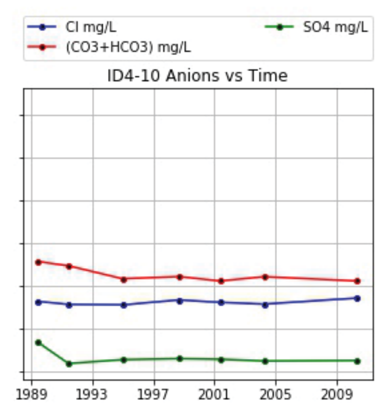

ID4-2
Mg^{2+}
SO_4^{2-}
Ca^{2+}
$Na^+ + K^+$ $HCO_3^- + CO_3^{2-}$
Cl^-
TDS mg/L
ID4-2 TDS vs Time
(Na+K) mg/L
Ca mg/L
Mg mg/L
ID4-2 Cations vs Time
Cl mg/L
(CO3+HCO3) mg/L
SO4 mg/L
ID4-2 Anions vs Time
0
100
200
300
400
500
1975 1979 1983 1987 1991 1995 1999 2003 2007 2011

11: ID4-10

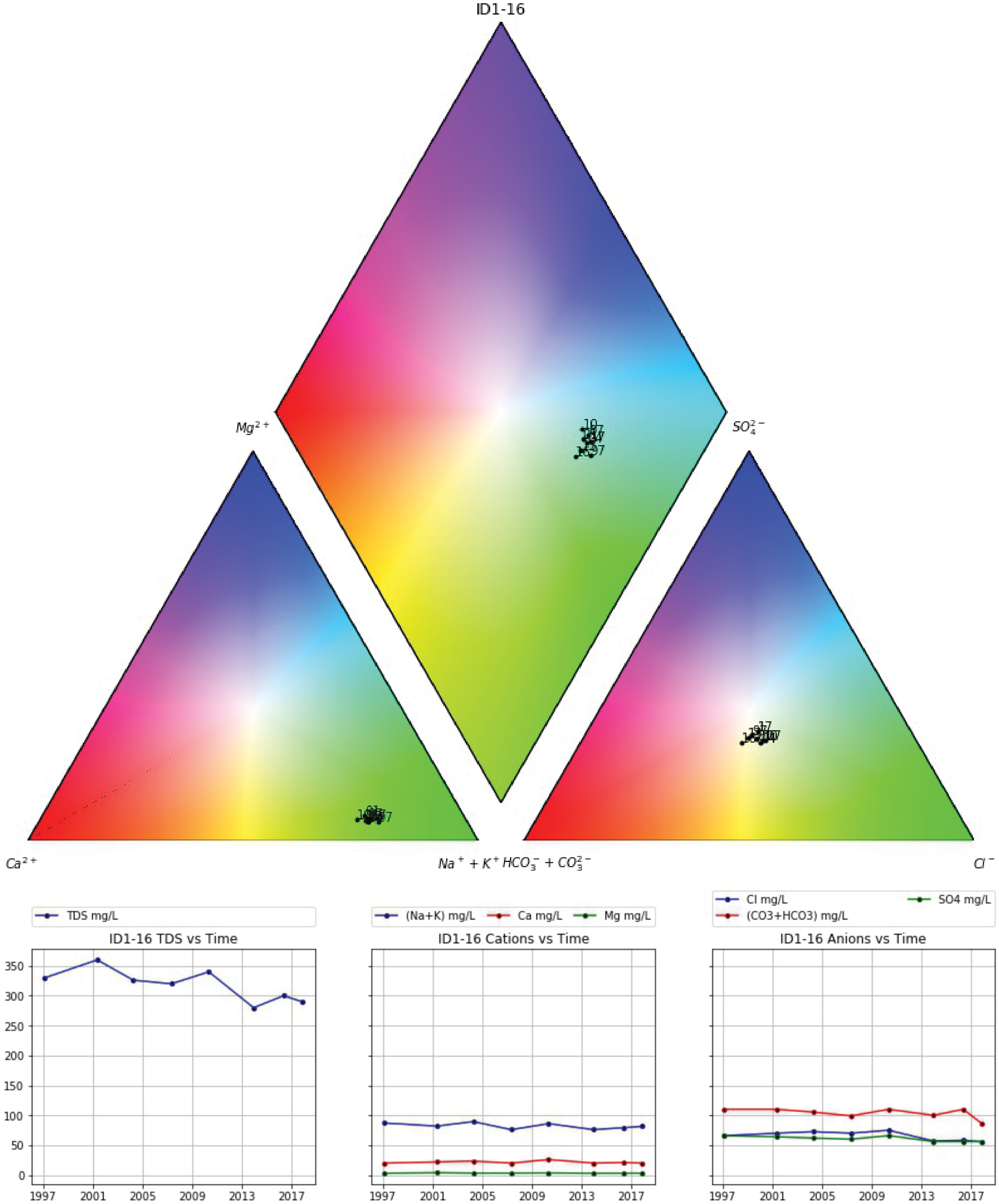

ID4-10
Mg^{2+}
SO_4^{2-}
Ca^{2+}
$Na^+ + K^+$ $HCO_3^- + CO_3^{2-}$
Cl^-
89
91
94
98
04
10


TDS mg/L
ID4-10 TDS vs Time
600
500
400
300
200
100
0
1989
1993
1997
2001
2005
2009

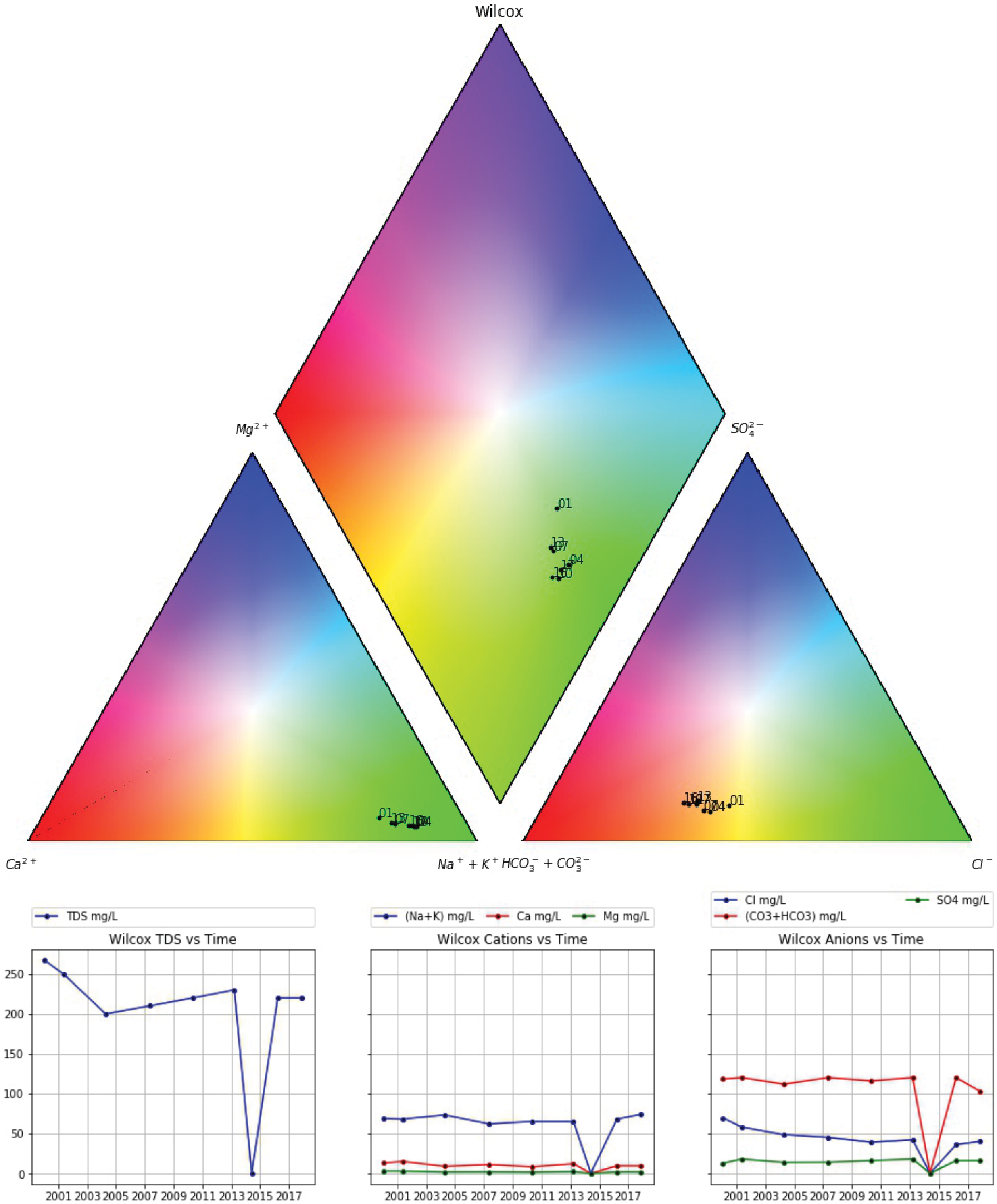

(Na+K) mg/L
Ca mg/L
Mg mg/L
ID4-10 Cations vs Time
1989
1993
1997
2001
2005
2009


Cl mg/L
(CO3+HCO3) mg/L
SO4 mg/L
ID4-10 Anions vs Time
1989
1993
1997
2001
2005
2009

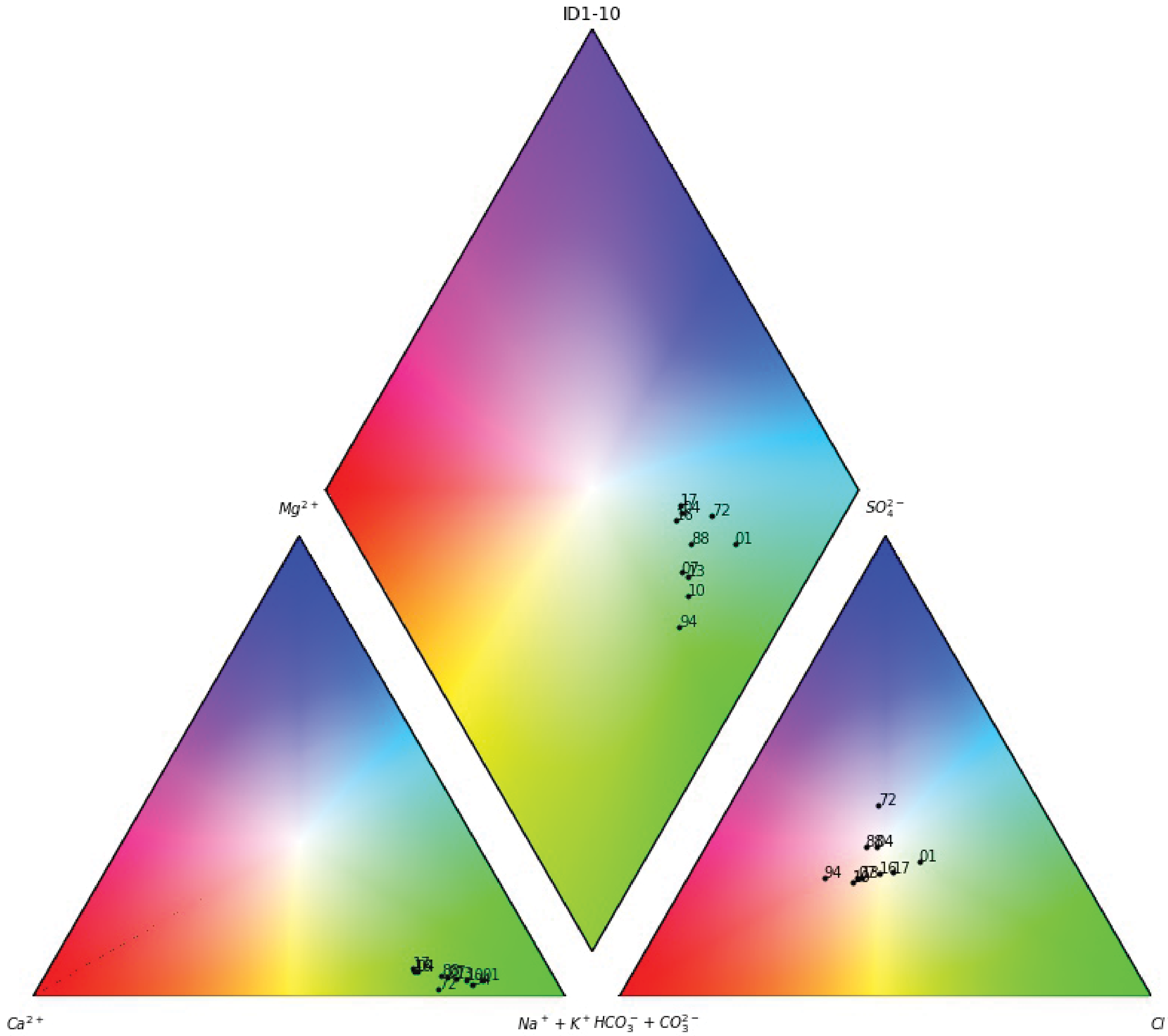
12: ID1-16

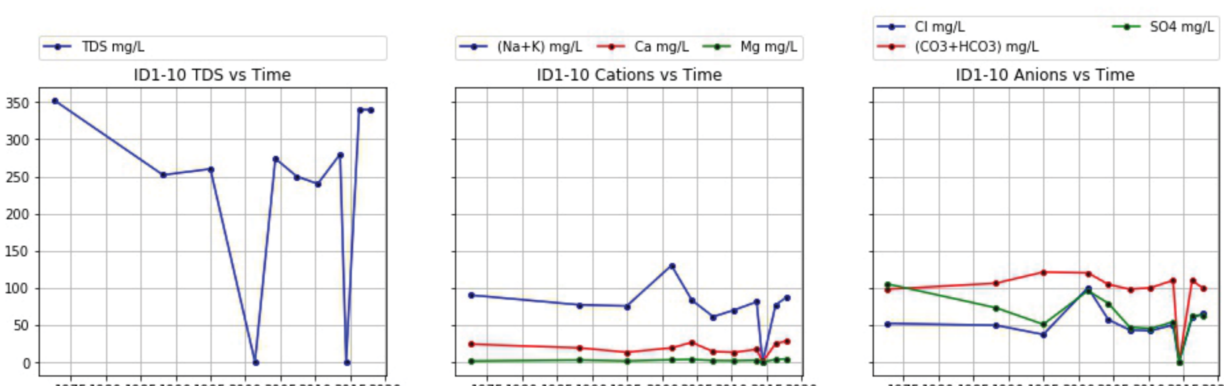

ID1-16
Mg^{2+}
SO_4^{2-}
Ca^{2+}
$Na^+ + K^+$ $HCO_3^- + CO_3^{2-}$
Cl^-
TDS mg/L
ID1-16 TDS vs Time
(Na+K) mg/L
Ca mg/L
Mg mg/L
ID1-16 Cations vs Time
Cl mg/L
SO4 mg/L
(CO3+HCO3) mg/L
ID1-16 Anions vs Time
350
300
250
200
150
100
50
0
1997
2001
2005
2009
2013
2017

13: Wilcox

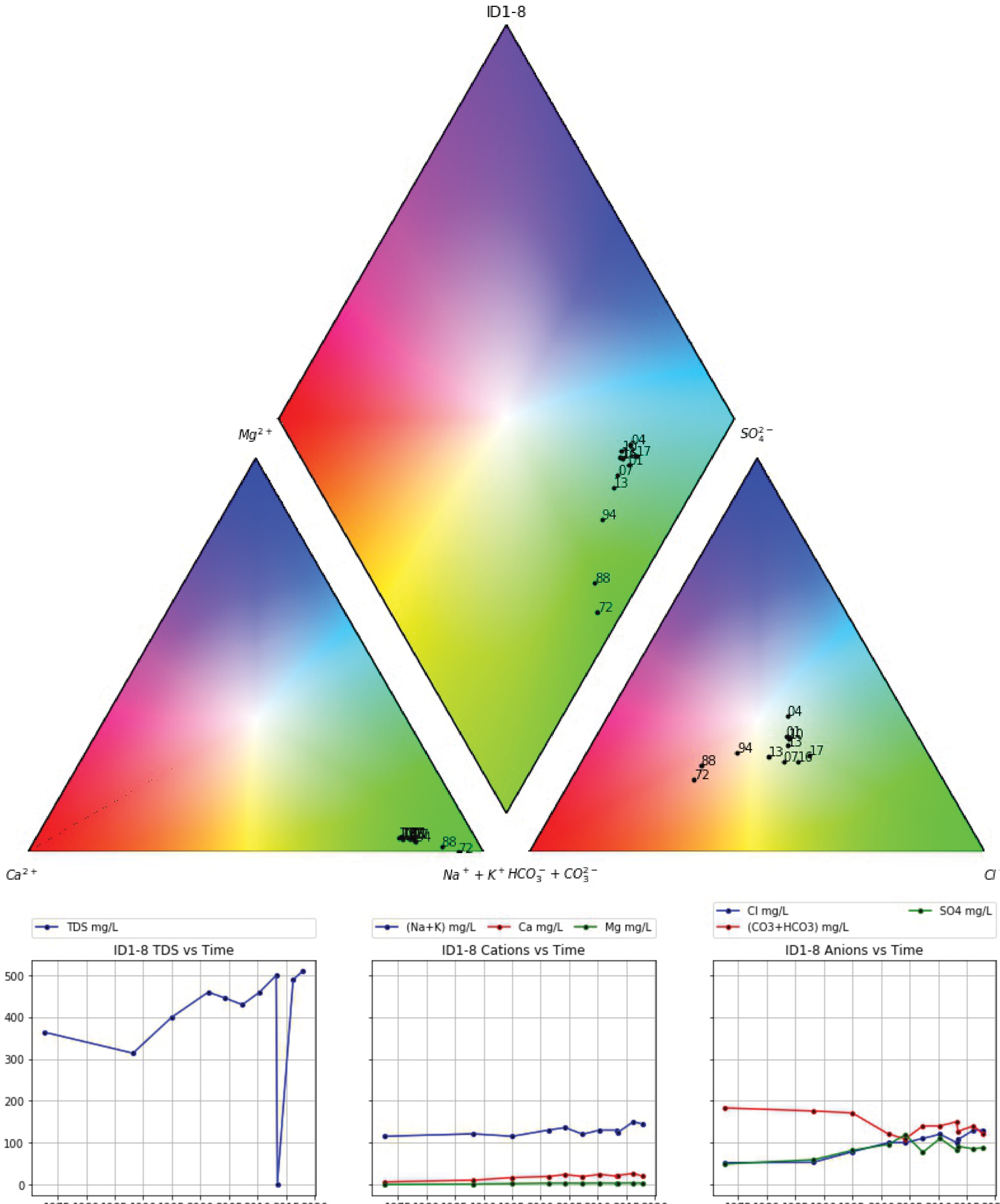

Wilcox
Mg^{2+}
SO_4^{2-}
Ca^{2+}
$Na^+ + K^+$ $HCO_3^- + CO_3^{2-}$
Cl^-
TDS mg/L
Wilcox TDS vs Time
(Na+K) mg/L
Ca mg/L
Mg mg/L
Wilcox Cations vs Time
Cl mg/L
(CO3+HCO3) mg/L
SO4 mg/L
Wilcox Anions vs Time
2001 2003 2005 2007 2009 2011 2013 2015 2017

14: ID1-10

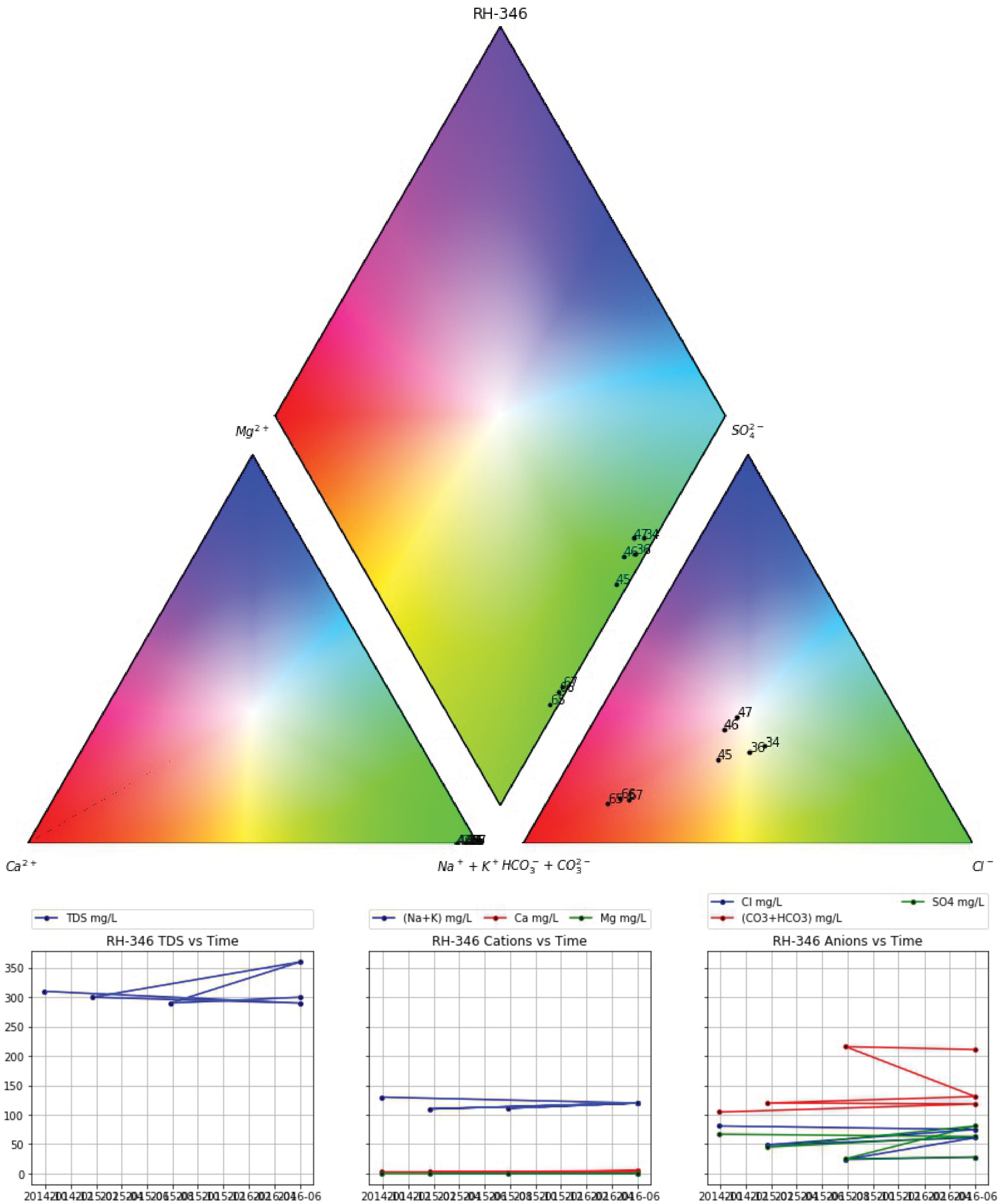

ID1-10
Mg^{2+}
SO_4^{2-}
Ca^{2+}
$Na^+ + K^+$ $HCO_3^- + CO_3^{2-}$
Cl^-


TDS mg/L
ID1-10 TDS vs Time
(Na+K) mg/L
Ca mg/L
Mg mg/L
ID1-10 Cations vs Time
Cl mg/L
SO4 mg/L
(CO3+HCO3) mg/L
ID1-10 Anions vs Time

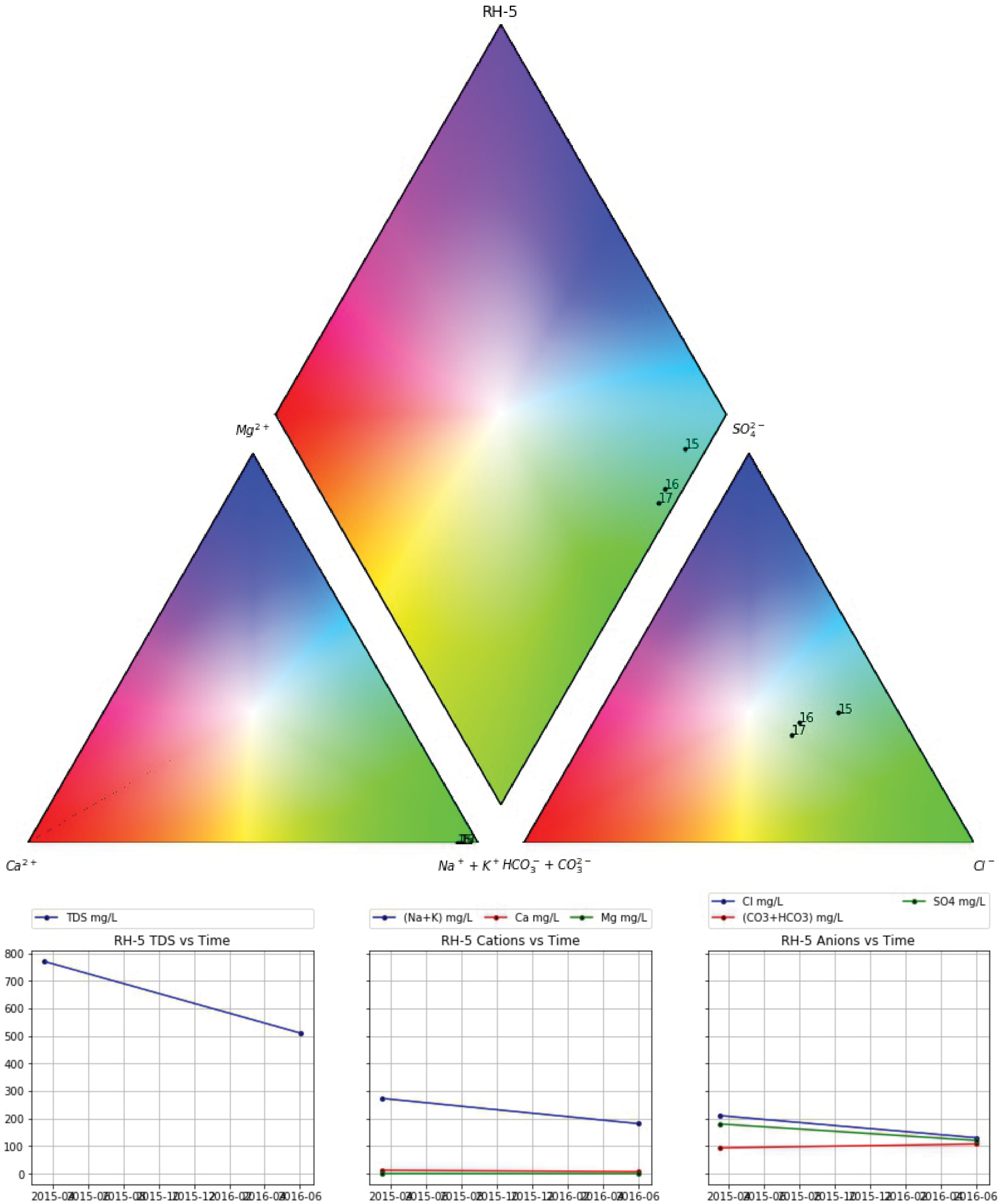
15: ID1-8


ID1-8
Mg^{2+}
SO_4^{2-}
Ca^{2+}
$Na^+ + K^+$ $HCO_3^- + CO_3^{2-}$
Cl^-
TDS mg/L
ID1-8 TDS vs Time
(Na+K) mg/L
Ca mg/L
Mg mg/L
ID1-8 Cations vs Time
Cl mg/L
SO4 mg/L
(CO3+HCO3) mg/L
ID1-8 Anions vs Time

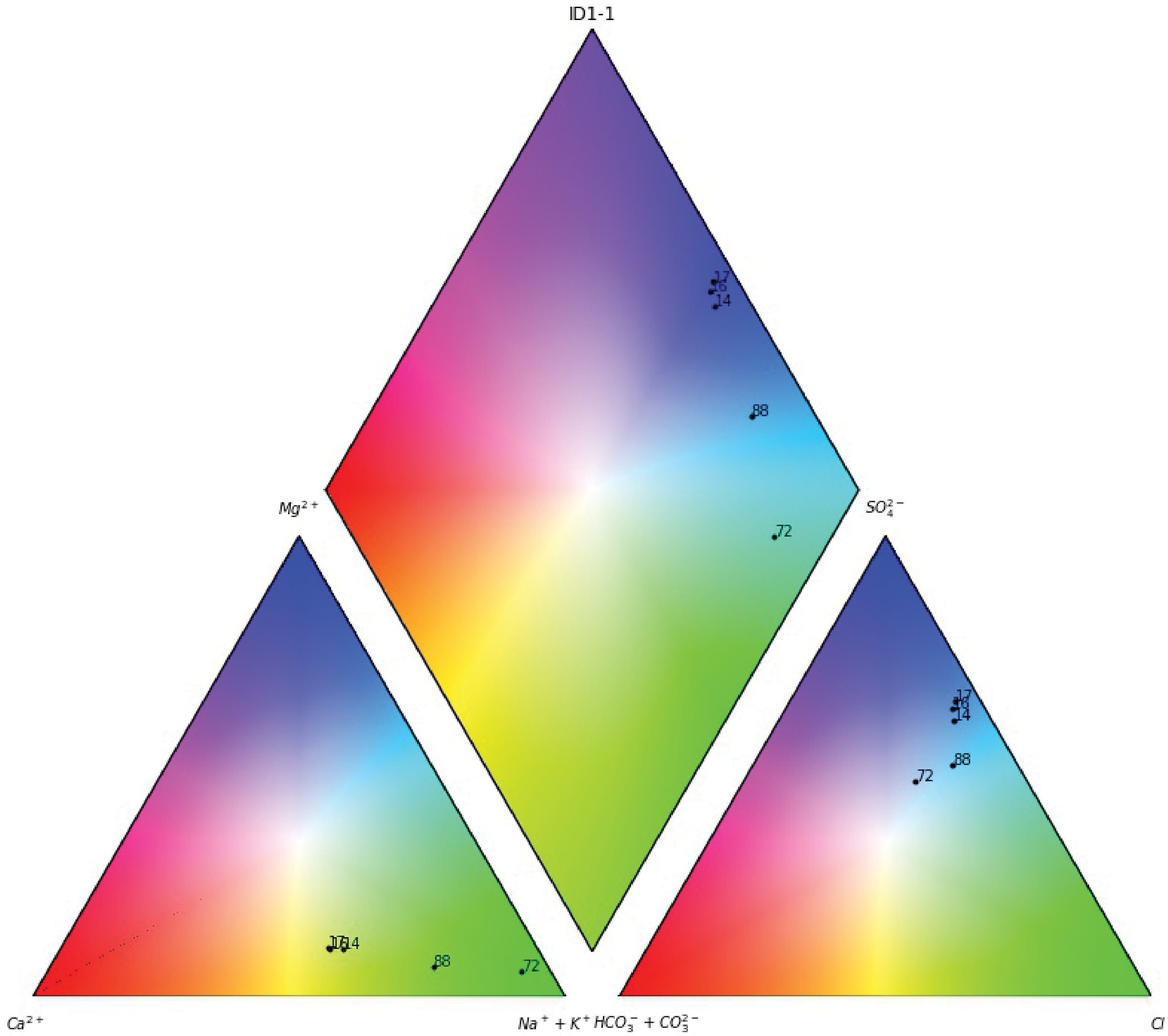
16: RH-3; 17: RH-4; 19: RH-6

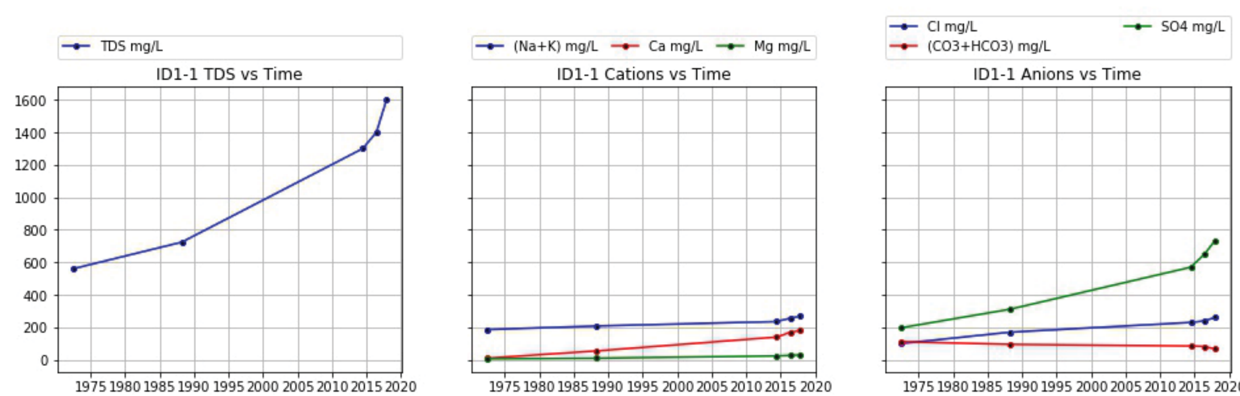


18: RH-5

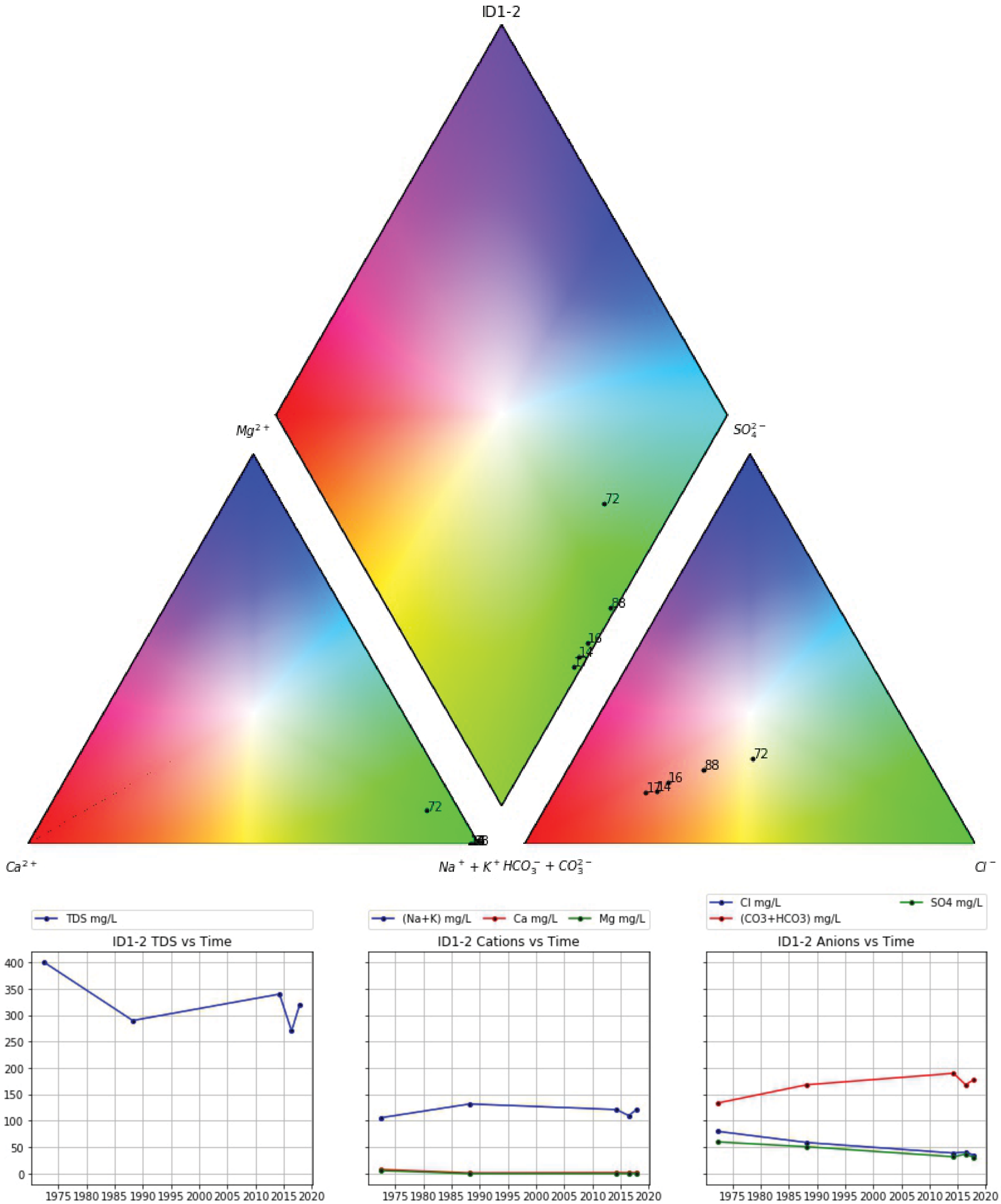

RH-5
Mg^{2+}
SO_4^{2-}
Ca^{2+}
$Na^+ + K^+$ $HCO_3^- + CO_3^{2-}$
Cl^-
15
16
17
TDS mg/L
RH-5 TDS vs Time
(Na+K) mg/L
Ca mg/L
Mg mg/L
RH-5 Cations vs Time
Cl mg/L
SO4 mg/L
(CO3+HCO3) mg/L
RH-5 Anions vs Time
800
700
600
500
400
300
200
100
0
2016-06

20: ID1-1

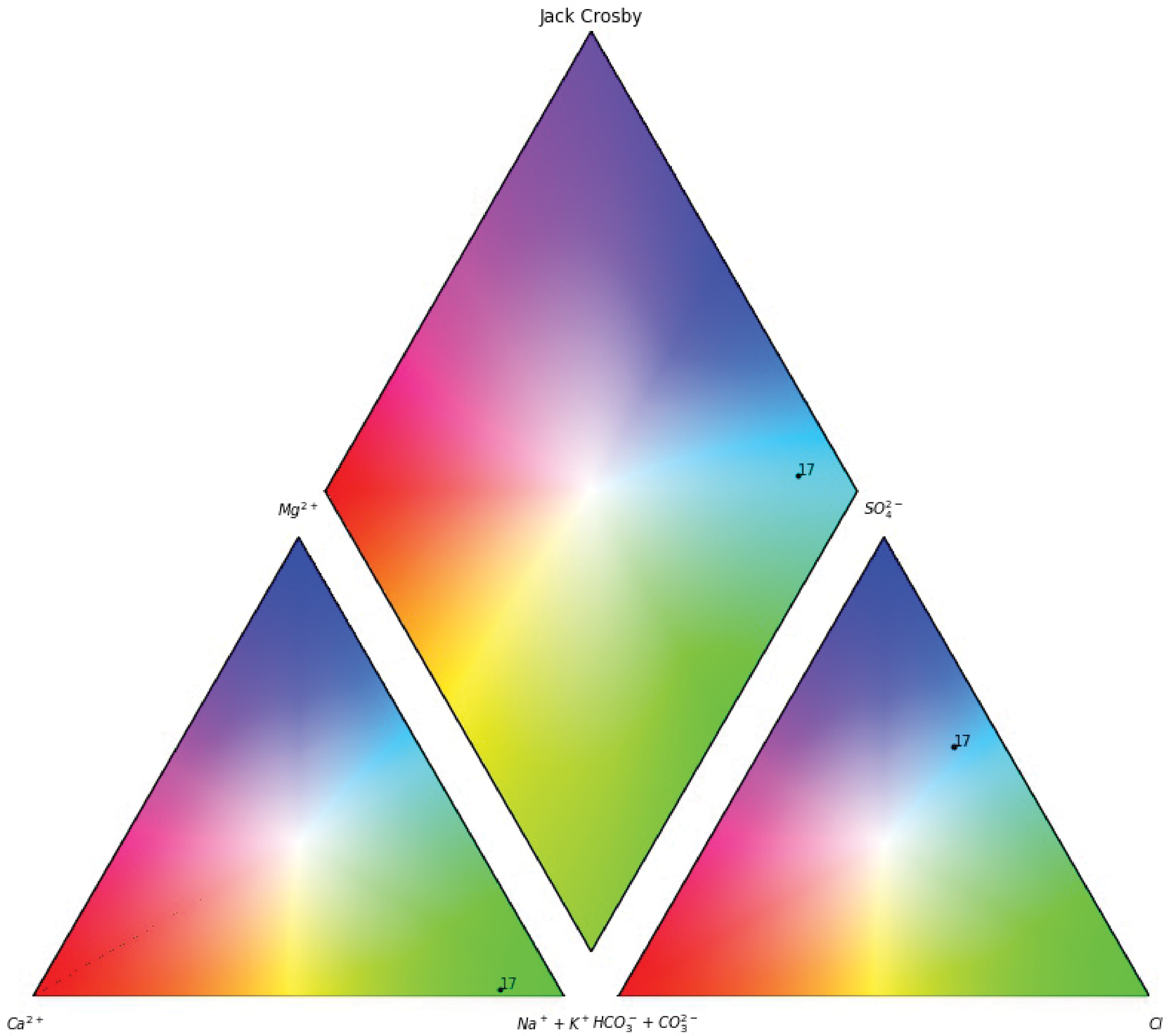

ID1-1
Mg2+
SO42-
Ca2+
Na+ + K+ HCO3- + CO32-
Cl-
17
16
14
88
72


TDS mg/L
ID1-1 TDS vs Time
(Na+K) mg/L
Ca mg/L
Mg mg/L
ID1-1 Cations vs Time
Cl mg/L
SO4 mg/L
(CO3+HCO3) mg/L
ID1-1 Anions vs Time
0
200
400
600
800
1000
1200
1400
1600
1975 1980 1985 1990 1995 2000 2005 2010 2015 2020

21: ID1-2

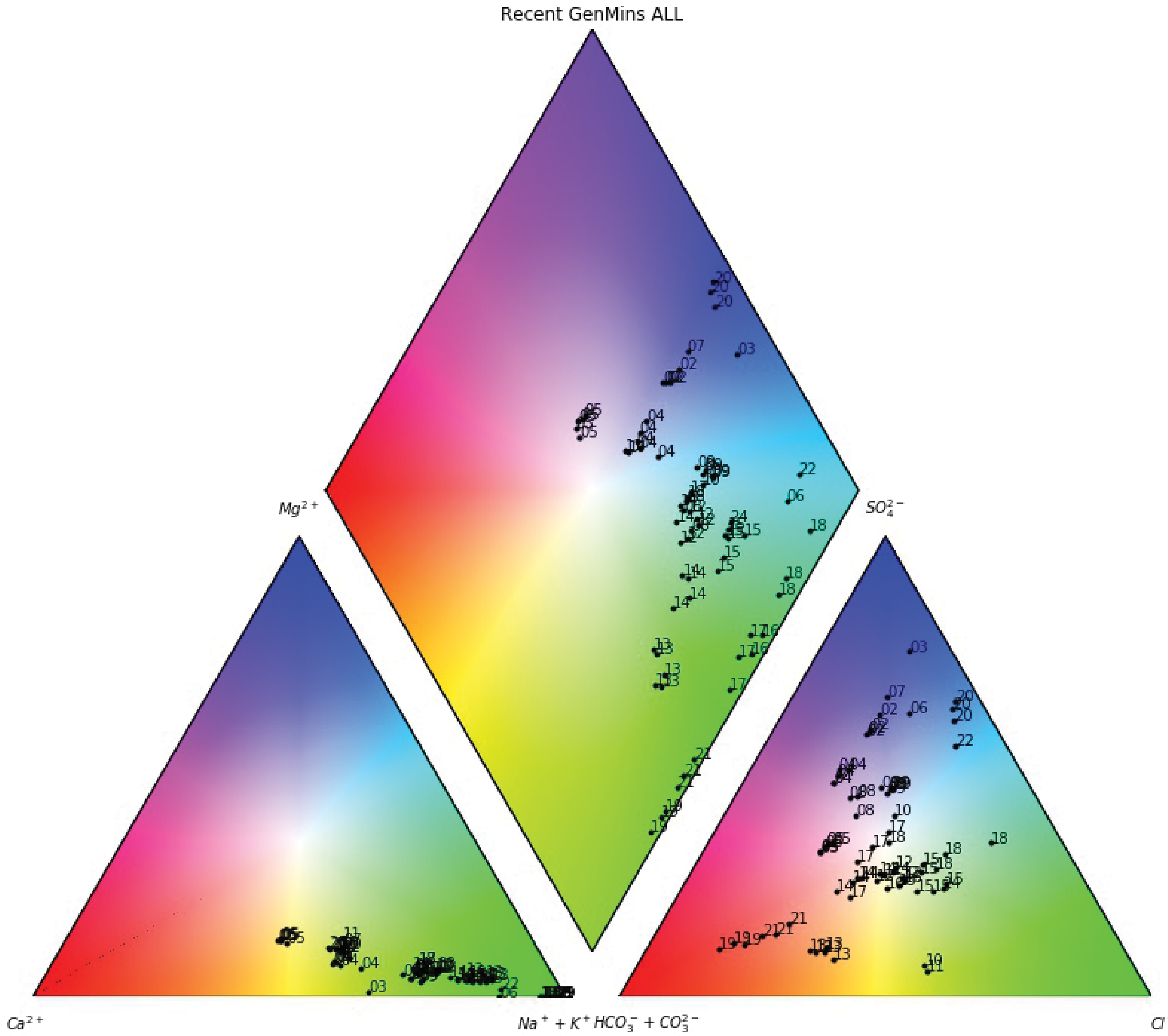

ID1-2
Mg^{2+}
SO_4^{2-}
Ca^{2+}
$Na^+ + K^+$ $HCO_3^- + CO_3^{2-}$
Cl^-
72
88
16
14
72
88
16
14
TDS mg/L
ID1-2 TDS vs Time
(Na+K) mg/L
Ca mg/L
Mg mg/L
ID1-2 Cations vs Time
Cl mg/L
SO4 mg/L
(CO3+HCO3) mg/L
ID1-2 Anions vs Time
400
350
300
250
200
150
100
50
0
1975 1980 1985 1990 1995 2000 2005 2010 2015 2020

22: Jack Crosby



One data point so no plots generated.

Recent Data: All (Piper only)

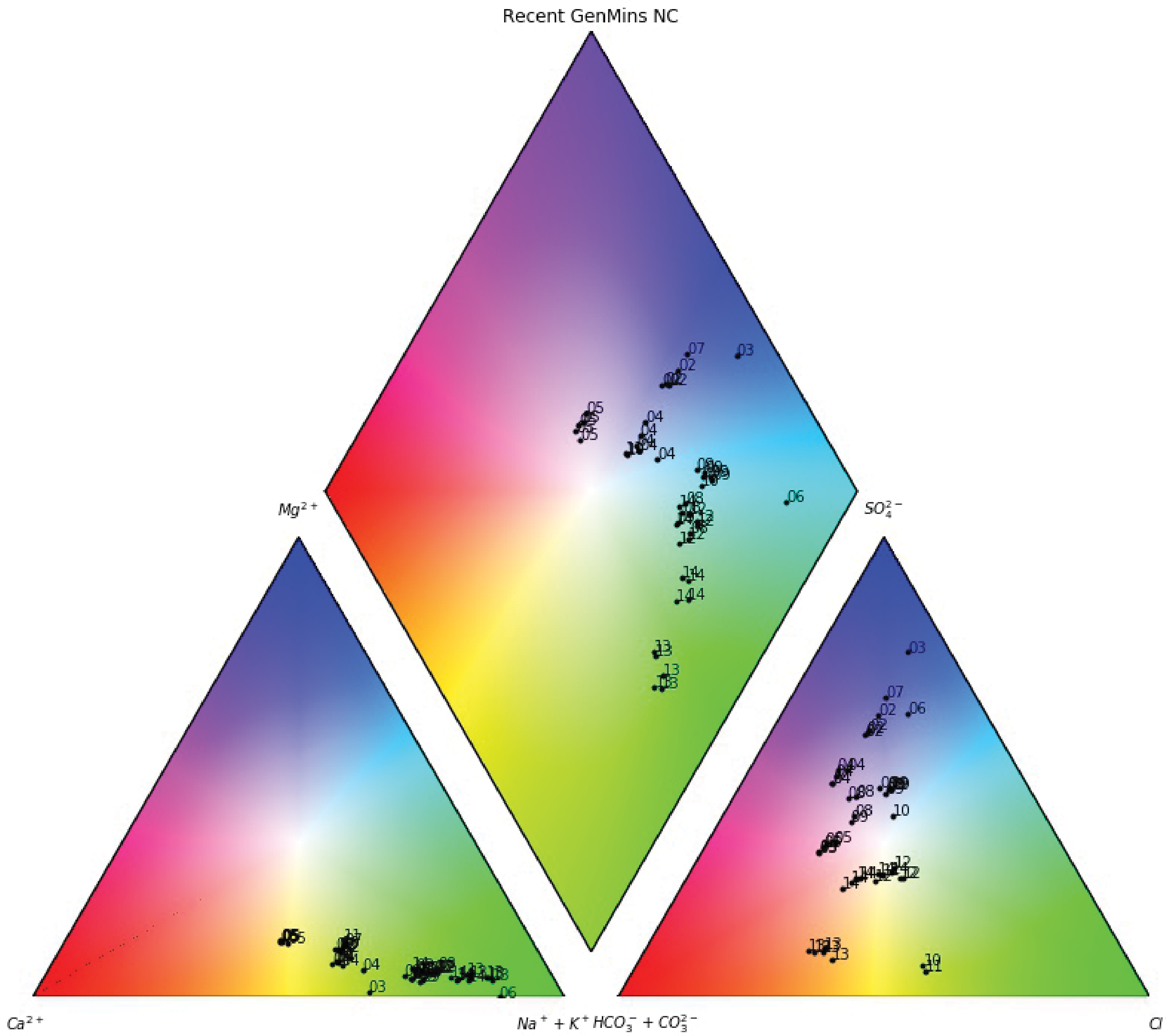


Notes:

The number on the diagrams correspond to sequential well numbers assigned to each of the wells as explained in the text. Data are for the period of 2005 to 2018.

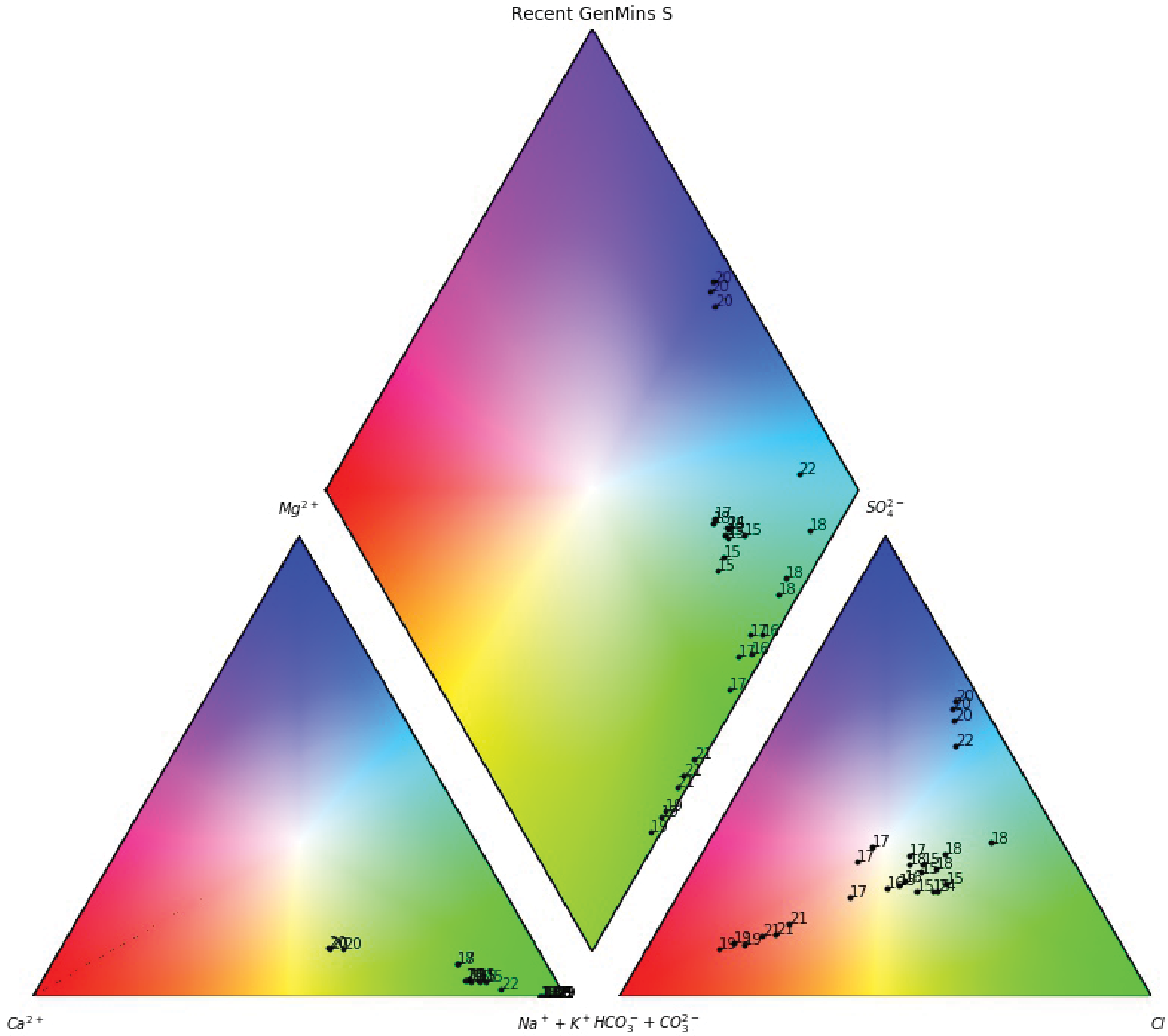
This Piper diagram is further explained in **Figure 6**.

Recent Data: North and Central (Piper only)



Note: The number on the diagrams correspond to sequential well numbers assigned to each of the wells as explained in the text. Data are for the period of 2005 to 2018.

Recent Data: South (Piper only)



Note: The number on the diagrams correspond to sequential well numbers assigned to each of the wells as explained in the text. Data are for the period of 2005 to 2018.