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TESTIMONY OF **ANTHONY BROWN** BEFORE THE SENATE COMMITTEE ON ENVIRONMENT AND PUBLIC WORKS ON THE APPROPRIATE ROLE OF STATES AND THE FEDERAL GOVERNMENT IN PROTECTING GROUNDWATER

APRIL 18, 2018

INTRODUCTION

Chairperson Barrasso, Ranking Member Carper, and Members of the Committee, my name is Anthony Brown and I am a hydrologist with **aquilogic**, an environmental and water resources consulting firm. I would like to thank you for the opportunity to testify on "The Appropriate Role of States and the Federal Government in Protecting Groundwater."

As stated, I am a hydrologist, and as such my professional focus is on the science and the engineering of water, in particular, the development, management and restoration of groundwater resources. I am currently working on projects in 10 States and, over the course of my more than 30 years of professional experience, I have worked on projects in an additional 12 States. My biographical sketch is attached hereto as **Appendix A**.

Unlike other witnesses you will hear from today, I am not a lawyer, lobbyist, regulator, or politician. My testimony will focus on the science and engineering of water, and will address the following key issues:

- The natural connection between groundwater and surface waters
- The contamination of groundwater by releases of pollutants
- The migration of this contamination with the movement of groundwater from the contaminant source to its discharge in proximate surface waters

HYDROLOGIC CONNECTION

Hydrologic Cycle

Groundwater and surface waters are part of the hydrologic cycle, or water cycle (**Figure 1**). As part of this cycle, precipitation that falls on the land flows to streams and other surface waters. Precipitation also infiltrates into the soil and percolates down to recharge the groundwater in aquifers. The groundwater flows laterally and vertically until it reaches a point of discharge, which can be to a man-made well or to surface waters. This is the natural course of water on, and beneath, the land surface.

Groundwater

Surface waters (streams, lakes, wetlands, etc.) are easier for a layperson to understand, as they can be seen, and are more easily monitored and tested. Whereas, groundwater lies beneath the ground and is more difficult to visualize, monitor, or test. In addition, the layperson is likely not aware that the volume of freshwater in aquifers far exceeds the total volume of surface waters. Only 2.5% of all water on earth is fresh water; the other 97.5% is salt or saline water (the oceans, etc.). Of the 2.5% that is fresh water, two-thirds of that is ice, almost one-third exists as groundwater in aquifers, and less than 1.2% is present as surface waters (**Figure 2**). Thus, groundwater aquifers contain 100 times more fresh water than all the lakes, rivers, swamps, and marshes on earth.

Aquifers

Groundwater is water that completely fills the pores and other spaces (e.g., fractures) within sediments (clays, sands, and gravels) and rocks (**Figure 3**). Sediments or rock strata that contain significant quantities of groundwater, permit the flow of groundwater, and yield water to wells, are referred to as aquifers. Sediments or rock strata that restrict flow and yield little or no water to wells are referred to as aquitards. In any geographic area, a series of aquifers and aquitards exist beneath the land surface. Aquifers are of two types: (1) unconfined or water table aquifers, where there is no overlying confining aquitard, and (2) confined aquifers that underlie an aquitard (**Figure 4**). The aquifers may extend thousands of feet below ground. Aquifers may also be localized or extend over thousands of square miles (**Figure 5**).

Pumping groundwater from aquifers provides a supply of reliable, high quality water for municipal, agricultural, and industrial purposes. Typically, where significant aquifers are present, strong agricultural economies have developed (e.g., the High Plains or Ogallala Aquifer, and the California Central Valley Aquifer system).

Groundwater Flow

As we know and can see, most surface waters (e.g., rivers, streams) flow downhill. In general, groundwater also flows downhill, away from areas of recharge, where precipitation infiltrates, to areas of discharge, such as surface waters. Specifically, groundwater flows from areas of high total head to low total head (**Figure 6**) down a hydraulic gradient. For groundwater in unconfined aquifers, the total head is simply the elevation of the water in the aquifer – usually measured as a water level in a well. For confined aquifers, total head is the elevation head plus the pressure head – how far the water will rise in a well above the top of an aquifer that is confined by an aquitard.

The direction and velocity of groundwater flow is controlled by numerous hydrogeologic factors, such as effective porosity (n_e), hydraulic conductivity (K), the volume of recharge, and the proximity of discharge. These factors need to be considered on a site-specific basis. However, nearly all groundwater must discharge at some point to a well or surface waters.

Darcy's Law

The volume of groundwater flow is defined by Darcy's Law:

$$Q = K.i.A$$

Where: Q = volume of discharge

K = hydraulic conductivity

i = hydraulic gradient

A = cross-sectional area of flow

To calculate flow volume, Henri Darcy envisioned groundwater flow in an aquifer as being through a conceptual sand-filled pipe (**Figure 7**). The hydraulic conductivity (K) is a term reflecting the ease by which the sediments in the conceptual pipe permit the flow of water (i.e., akin to a resistance or friction term). The gradient (i) is the difference in head across the pipe with a defined cross-sectional area (A). Thus, groundwater flow can be viewed as flow through a sand-filled pipe or flow through millions of tortuous pipes that run between the sediment grains. Given the resistance posed by the aquifer materials, groundwater flow is much slower than the flow in streams or rivers. Streams may flow many miles in a day; whereas, groundwater in an aquifer usually only flows at hundreds of feet per year. As noted, the parameters needed to determine groundwater velocities and flow volumes are site-specific and analysis of local conditions is required.

Discharge to Surface Waters

Stream flow consists of two elements: baseflow and storm flow (**Figure 8**). Baseflow is relatively constant and is sustained by the discharge of groundwater into the stream. Storm flow is intermittent and results from direct precipitation and overland runoff into the stream during a storm event.

In most settings, the hydraulic head for groundwater proximate to surface waters is higher than the water level in the adjacent stream or lake (**Figure 9**). Thus, groundwater flows from higher to lower hydraulic head and eventually discharges into the surface waters. In rivers, these surface waters are often referred to as gaining streams. In some instances, notably in arid climates where flow in a stream may be ephemeral, the groundwater level may be lower than the water level in the stream when there is stream flow. In these circumstances, water flows from the stream, downward through the streambed, and recharges groundwater. These are often referred to as losing streams. For any stream it may have both losing and gaining sections at various locations along its length, and it may be losing or gaining at various times of the year in any given location. For tidal water bodies, the streams may be losing and gaining at different times of the day, resulting in what is referred to as tidal-pulsing of groundwater flow.

CONTAMINATION OF GROUNDWATER

Types of Pollutants

Pollutants can be divided by their chemical character: organic chemicals, inorganic chemicals, radionuclides, and bacteriological. A listing of common and emerging groundwater pollutants can be found at: http://www.aquilogic.com/COCs.php, and includes:

- Petroleum Contaminants
- Fuel Oxygenates
- Oil Field Contaminants
- Coal Combustion Products
- Chlorinated Solvents
- 1,4-Dioxane
- Freon Compounds
- Agricultural Chemicals
- GenX
- DBCP and other soil fumigants
- 1,2,3-TCP
- Perchlorate
- NDMA
- Hexavalent Chromium
- Trace Metals
- Unregulated Chemicals
- PPCP's
- Perfluorinated Compounds
- Brominated Flame Retardants
- Wood Preservatives

A periodic table of common water pollutants is provided as **Figure 10**.

For water contamination, as in toxicology, dose makes the poison. Small releases of highly toxic chemicals, such as perfluorinated chemicals (PFCs), can create more water pollution than larger releases of less toxic chemicals, such as diesel fuels. The toxicity of a pollutant, when regulated, is reflected in the Federal maximum contaminant level goal (MCLG), MCL, or surface water quality standard. These levels are usually expressed as concentrations in parts per million, parts per billion, and in some cases, parts per trillion.

Regulatory Levels

The USEPA has adopted MCLs for 87 pollutants and surface water quality criteria for about 120 pollutants, and 109 pollutants are on the contaminant candidate list (CCL4). Most of these are organic chemicals, such as benzene and tetrachloroethene (i.e., PCE or dry cleaning solvent), inorganic elements, such as arsenic and nitrate, or different types of bacteria. However, according to the USEPA's Toxic Substances Control Act (TSCA) Inventory, there are over 85,000 chemicals in commercial use within the United States, as of April 2018. Therefore, more than 99% of all chemicals have not been regulated.

Many regulatory programs define violations and clean-up relative to these MCLs or similar standards; therefore, most pollutants are inadequately addressed. Whereas, some regulatory actions, such as those under the Clean Water Act, define violations and clean-up above a background concentration. Thus, they address any pollutant above its natural concentration, rather than just those with established Federal standards.

Sources of Pollution

Nearly all sources of water contamination are located on land, and are usually underlain by groundwater. Whereas, not all sources of contamination are located immediately proximate to surface waters. Thus for pollutant releases distant from surface waters, the pollutant will impact groundwater long before it ever reaches surface waters, if it ever does. Even proximate to surface waters, releases of pollutants are more likely to impact groundwater before they impact surface waters.

Pollutant sources can be divided into two broad categories: point source pollutants and non-point source pollutants. Point sources of pollution include refineries, chemical plants, aerospace facilities, metal platers, dry cleaners, service stations, mines, landfills, cattle feed lots, sewage lagoons, and coal ash impoundments. Releases at these facilities can result from the storage, use, transport, and disposal of chemicals or wastes, and are often associated with leaks from tanks, sumps, pipes, pits, impoundments, landfills, etc. Non-point sources are dispersed over wide areas, such as the agricultural application of fertilizers or pesticides, urban runoff, or atmospheric deposition of airborne pollutants.

CONTAMINANT MIGRATION

Once pollutants mix with the flowing groundwater, they will move with that groundwater (**Figure 11**). As noted, groundwater flow is quite slow compared to surface water; therefore, contaminant migration will also be relatively slow. Over years (or even decades), many inorganic pollutants (e.g., perchlorate) and some organic pollutants (e.g., TCE, PFCs, MTBE) may form contaminant plumes that are many miles long (**Figures 12 and 13**). However, most pollutants are unlikely to migrate great distances in groundwater (i.e., many miles) due to natural physical, chemical and biological processes in the subsurface that retard their transport, notably dilution and dispersion. This is referred to as natural attenuation.

The distribution of contaminant concentrations in groundwater, the rate of migration, the total distance of migration, and the persistence of the contaminant plume, are dependent on numerous factors, including the location, size and timing of the pollutant release, the hydrogeologic conditions (e.g., groundwater flow direction and velocities), the chemical properties of the pollutants (e.g., solubility, adsorption coefficient), and the effectiveness of various natural attenuation processes. Given the complexity of hydrogeologic and contaminant conditions, the migration of pollutants in groundwater, and their discharge to proximate surface waters, has to be evaluated on a site-specific basis.

CONTAMINANT DISCHARGE

As noted, in general, groundwater proximate to surface waters will discharge to those waters. Also, as noted, any pollutant dissolved into groundwater will migrate with the groundwater. For many pollutants, the distance migrated by the contaminant plume will be limited by natural attenuation. Therefore, in general, only releases of pollutants into groundwater proximate to surface waters, migrate all the way to, and discharge to, the surface waters (**Figure 14**).

The discharge of contaminated groundwater to surface waters can occur via two primary mechanisms: seeps along the banks of the surface water body, and bed seepage through the bottom of the surface water body (**Figure 15**). Seeps occur above the surface water line; whereas, bed seepage occurs below the surface water line.

INVESTIGATION OF DISCHARGE

An assessment of the discharge of pollutants dissolved in groundwater into surface waters requires a site-specific investigation. Where the pollutants are detected in surface water samples adjacent to, and/or downstream of the contaminated groundwater, but not upstream in the surface waters, it is clear that the pollutant is discharging to surface waters from the groundwater. Where pollutants are not detected in surface water samples due to dilution resulting from the mixing of groundwater and the surface water flows, it can still be reasonably inferred that the pollutant in groundwater is discharging to surface waters, when:

- The groundwater level in monitoring wells installed proximate to the surface waters is higher than the surface water level and the groundwater contains pollutants, or
- The pollutants are detected in water-saturated sediments along the surface water bank or in the bed of the surface water body, or
- The pollutants are detected in sediment “pore water” adjacent to, or below, the surface water body (i.e., groundwater in the sediments)

REMEDIATION, RESTORATION AND MITIGATION

Remediation refers to the clean-up of pollution to a water quality standard or criterion, such as an MCL, or a risk-based level. These standards or levels may be above background concentrations. Restoration refers to the clean-up of pollution to background concentrations or a pre-discharge condition. Mitigation refers to the prevention of discharge rather the remediation or restoration of the contamination.

Remediation and restoration usually include a source clean-up in the area where the release occurred, and plume clean-up and/or plume control; whereas, mitigation may only include plume control. The most effective source clean-up is the complete removal of the contaminated source area; however, other approaches can also be used for certain pollutants and contaminant sources (e.g., soil vapor extraction for volatile pollutants). Plume clean-up can be accomplished by ex-situ (out of the ground) technologies (e.g., pump-and-treat) or in-situ (in the ground) technologies (e.g., in-situ chemical oxidation). Likewise, plume control can also be accomplished using ex-situ technologies (e.g., pump-and-treat) and in-situ technologies (e.g., permeable reactive barriers).

REGULATORY CLEAN-UPS

Clean-up of contaminated groundwater is often directed using one of four statutory authorities:

- The Comprehensive Environmental Response, Compensation and Liability Act (CERCLA) or State equivalents
- The Resource Conservation and Recovery Act (RCRA) or State equivalents
- The Federal leaking underground storage tank (LUST) Trust Fund Program, or State equivalents
- A natural resource damage assessment (NRDA) and associated mitigation and/or restoration

Clean-ups under the first three statutory authorities are usually remediation programs with a defined remediation goal based on a regulatory standard/criterion or a risk-based level. These clean-ups target the groundwater contamination itself rather than the discharge of that contamination to surface waters. However, for a variety of reasons, there are still tens of thousands of groundwater contaminant plumes across the nation that have yet to be fully remediated under these enforcement mechanisms. For example, numerous states have filed state-wide claims for MTBE contamination that still persists more than a decade after the use of this chemical was banned by many States. These state-wide claims include thousands of release sites and associated groundwater contaminant plumes. As a further example, investigation and remediation actions are still ongoing at hundreds of Federal Superfund sites many decades after these sites were included on the National Priorities List.

Clean-ups under an NRDA are often restoration programs with a restoration goal established at background concentrations or pre-discharge conditions. Under most circumstances, the trustees (Federal and/or State regulatory agencies) direct the NRDA; however, given the costs associated with the NRDA investigation, NRDA directed clean-ups are rare.

Court rulings have found that discharges of pollutants from point sources to surface waters that travel via hydrologically connected groundwater are a violation of the Clean Water Act. Therefore, while the Clean Water Act may not provide statutory authority to require remediation or restoration of the groundwater contaminant plume, it clearly does require the remediation of the discharge to surface waters. However, the removal of the source, and plume remediation, may be the best way to remediate the discharge.

CURRENT EXAMPLES OF POLLUTANT DISCHARGE TO SURFACE WATERS

The following are some recent news articles about pollutants migrating with groundwater and discharging to surface waters (**Figure 16**):

- Sticky Piles Of Toxic PFAS Foam Plaguing Michigan Lake - http://www.mlive.com/news/index.ssf/2018/02/wurtsmith_pfas_foam_michigan.html
- Beneath The Surface: Controversy On The Buffalo National River - https://www.417mag.com/issues/november-2017/beneath-the-surface-controversy-on-the-buffalo-national-river/
- Study Links Groundwater With Surface Water In Devils River - https://phys.org/news/2017-08-links-groundwater-surface-devils-river.html
- Mayor: City Wants To Ensure Coakley 'Isn't Poisoning Anyone' - http://www.seacoastonline.com/news/20180403/mayor-city-wants-to-ensure-coakley-isnt-poisoning-anyone
- Fish And Game: Don't Eat Fish From Berry's Brook - http://www.seacoastonline.com/news/20180321/fish-and-game-dont-eat-fish-from-berrys-brook
- Oscoda Toxic PFC Groundwater Plumes Approaching Lake Huron - http://www.mlive.com/news/index.ssf/2016/09/oscoda_toxic_groundwater_plume.html
- EPA To Consider Superfund Cleanup Of Ann Arbor's Toxic Groundwater - http://www.mlive.com/news/ann-arbor/index.ssf/2017/02/epa_to_look_at_ann_arbor_chemi.html
- Professor Says Dioxane Probably Has Reached Huron River Already - http://www.mlive.com/news/ann-arbor/index.ssf/2016/05/professor_says_dioxane_plume_m.html

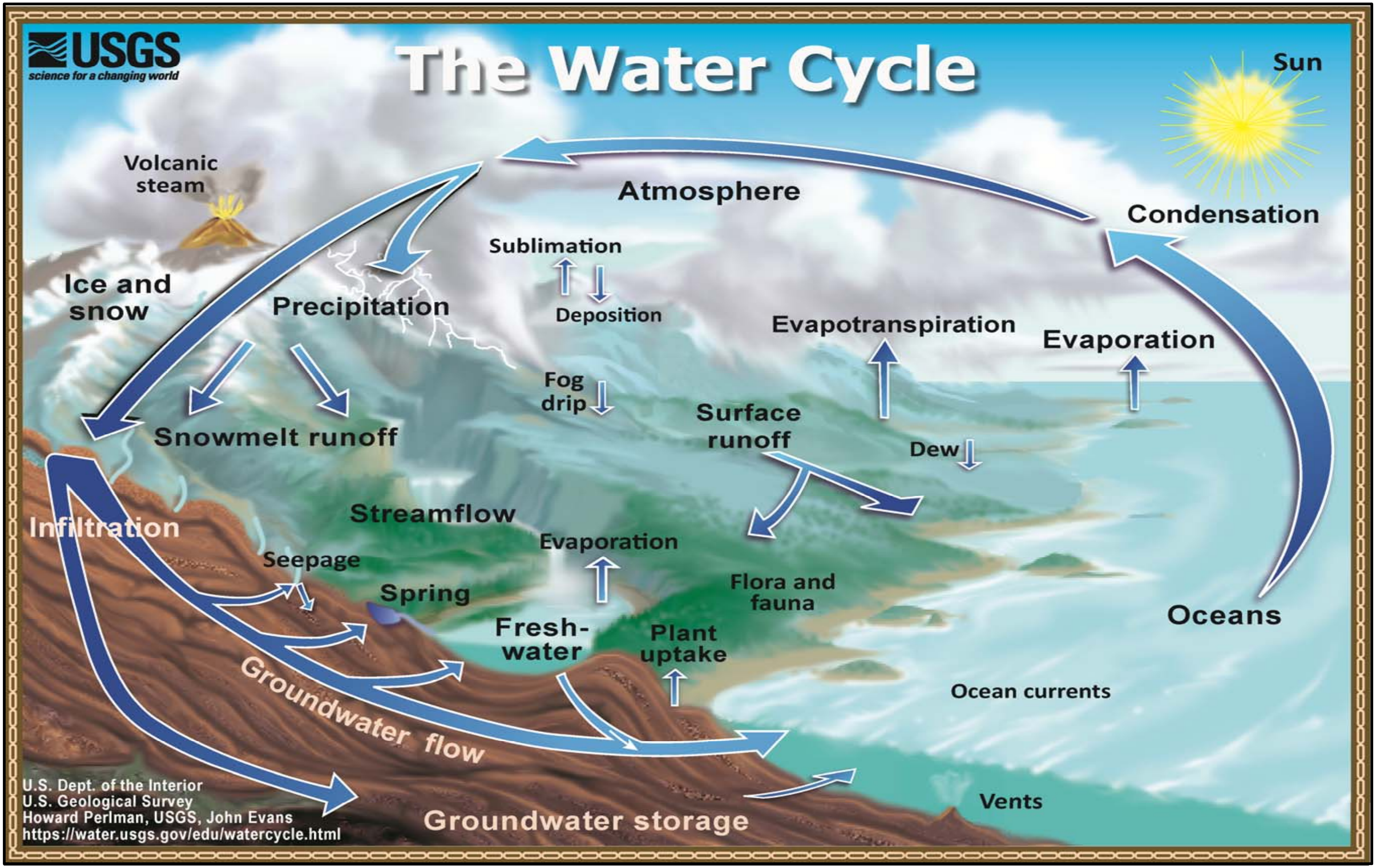
- Northern Michigan Community Tries To Stay Ahead Of Massive Contaminated Plume - http://michiganradio.org/post/northern-michigan-community-tries-stay-ahead-massive-contaminated-plume
- Radioactive Waste Still Flooding Columbia River, EPA Says - https://www.courthousenews.com/radioactive-waste-still-flooding-columbia-river-epa-says/
- Extremely High PFAS Levels Found At Wolverine Tannery Site - http://www.mlive.com/news/grand-rapids/index.ssf/2017/11/extremely_high_pfas_levels_fou.html
- Rockford May Have Been Drinking Contaminated Water Before 2000 - http://www.mlive.com/news/grand-rapids/index.ssf/2018/01/pfas_rockford_water_wolverine.html
- Polluted Groundwater Seeping Into The Bound Brook, Posing Costly Cleanup Challenges - http://www.nj.com/middlesex/index.ssf/2014/05/bound_brook_pollution_epa.html
- Contaminated Water Open House Draws Crowd In Fairbanks - http://www.newsminer.com/news/local_news/contaminated-water-open-house-draws-crowd-in-fairbanks/article_f90bb8da-2760-11e8-a68e-534c1e36749f.html
- EPA To Consider Superfund Cleanup Of Ann Arbor's Toxic Groundwater - http://www.mlive.com/news/ann-arbor/index.ssf/2017/02/epa_to_look_at_ann_arbor_chemi.html
- PG&E Begins Pumping Toxic Groundwater Away From Colorado River - https://www.wqpmag.com/pge-begins-pumping-toxic-groundwater-away-colorado-river
- Colorado River At Risk - https://lasvegassun.com/news/2007/may/27/colorado-river-at-risk/
- PG&E Nears Plan To Filter Chromium On Colorado River, Could Take 30 Years To Decontaminate - http://www.havasunews.com/news/pg-e-nears-plan-to-filter-chromium-on-colorado-river/article_8dd25af6-f20c-11e4-8665-5f980b3b9e65.html
- LOIS HENRY: Pollution Plumes Stopped By Drought But How Much Longer For Cleanup? - http://www.bakersfield.com/columnists/lois-henry-pollution-plumes-stopped-by-drought-but-how-much/article_c912036c-a3b4-5f1d-87a2-0fc818910dcb.html
- Environmental Groups Continue Fight Against Kinder Morgan After Fourth Circuit Revives Federal Lawsuit - https://greenvillejournal.com/2018/04/13/environmental-groups-continue-fight-against-kinder-morgan-after-fourth-circuit-revives-federal-lawsuit/
- Firefighting Foam Used By Unit Of Johnson Controls Poses Toxic Threat To Green Bay - https://www.jsonline.com/story/news/politics/2018/03/19/firefighting-foam-used-unit-johnson-controls-poses-toxic-threat-green-bay/427678002/

CONCLUSION

In most situations, groundwater will discharge to proximate surface waters. If pollutants are released and impact groundwater proximate to the surface waters, then the pollutants will be transported via groundwater where they will subsequently discharge to the surface waters. Court rulings have found that these types of discharges are a violation of the Clean Water Act when they fall within the Act's terms and must be remedied.

Thank you for the opportunity to testify. I am happy to answer any of your questions.

ACCOMPANYING FIGURES



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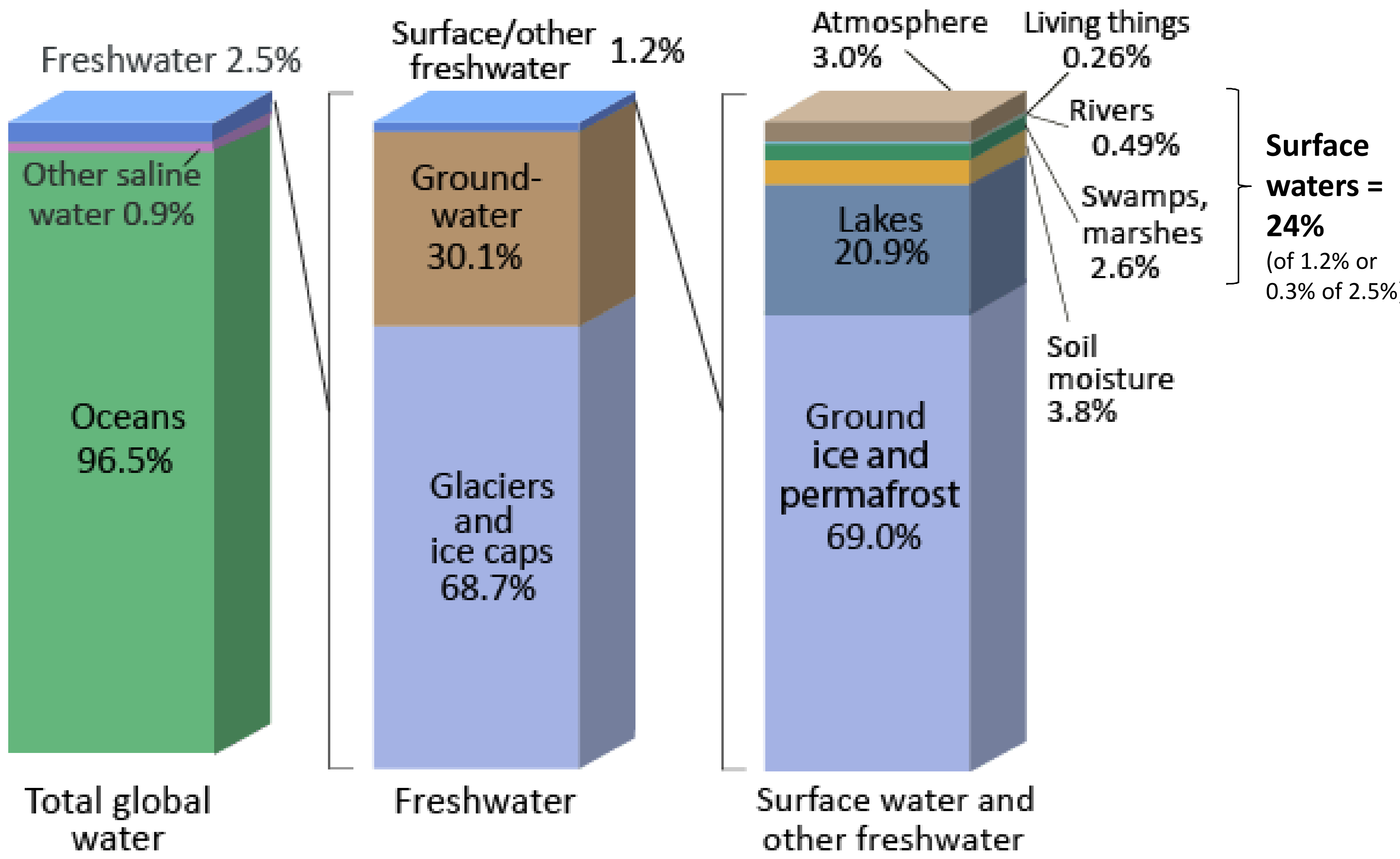
The Water Cycle

https://water.usgs.gov/edu/watercycle.html

Date: 4/16/2018	Project # NA:	**Figure 1**



Source: Igor Shiklomanov's chapter "World fresh water resources" in Peter H. Gleick (editor), 1993, Water in Crisis: A Guide to the World's Fresh Water Resources.
NOTE: Numbers are rounded, so percent summations may not add to 100.

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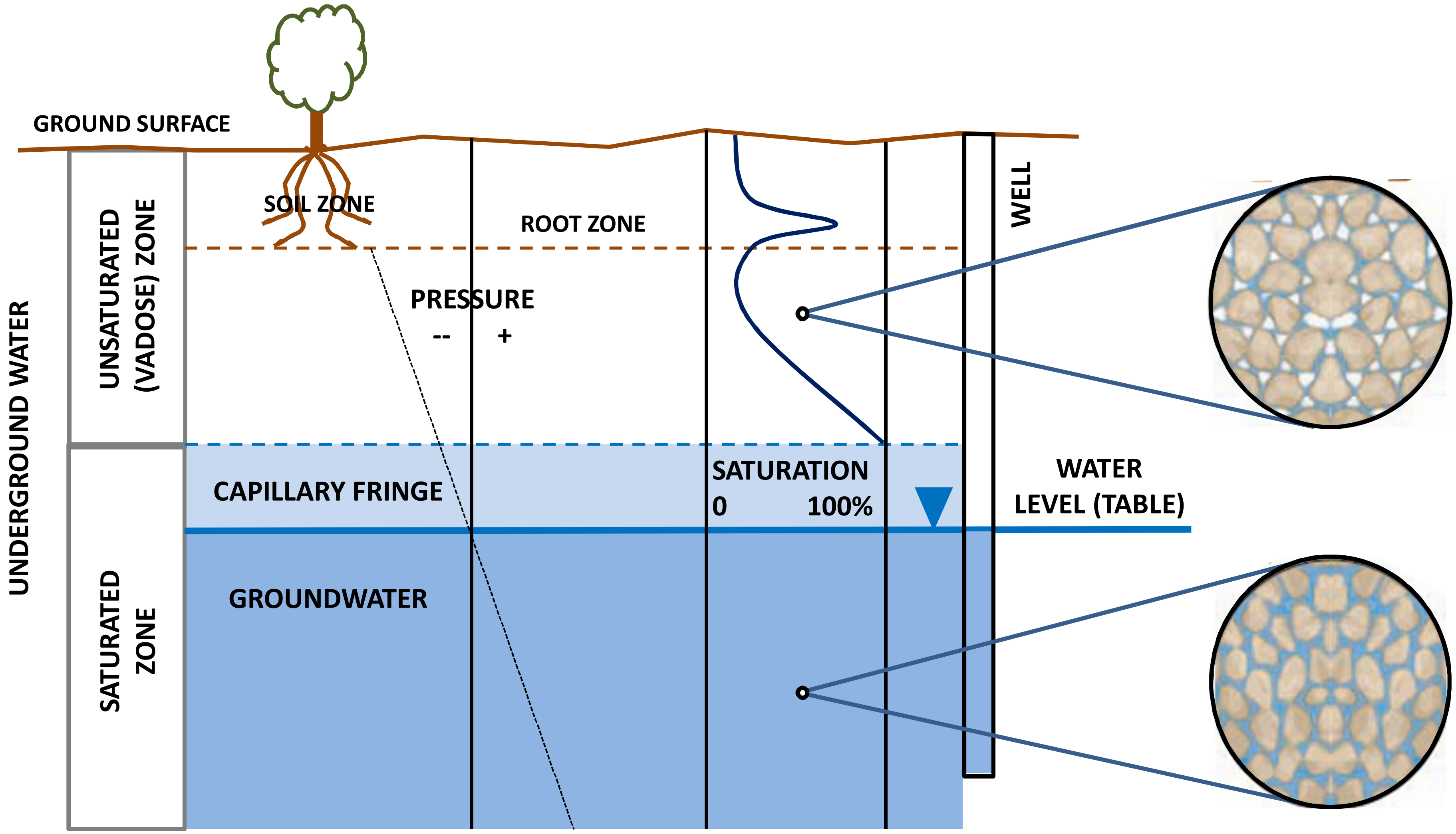
Distribution of Water on Earth

Date: 4/16/2018	Project # NA:	**Figure 2**



modified from Heath (1983), Basic Ground-Water Hydrology. USGS Water Supply Paper 2220

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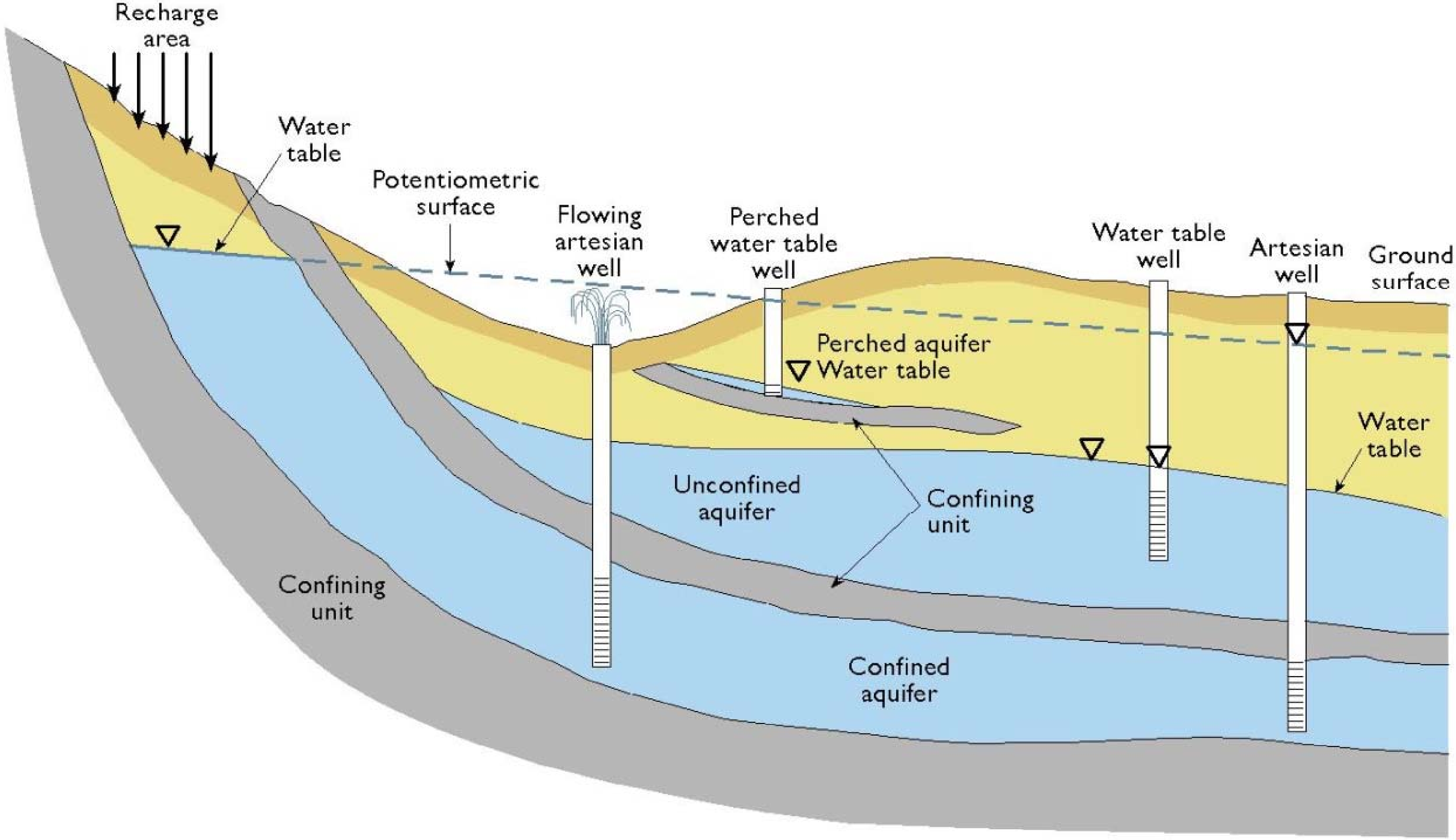
Underground Water

Date: 4/16/2018	Project # NA:	**Figure 3**



Colorado Geological Survey. (2003). Groundwater Atlas of Colorado. Special Publication 53.

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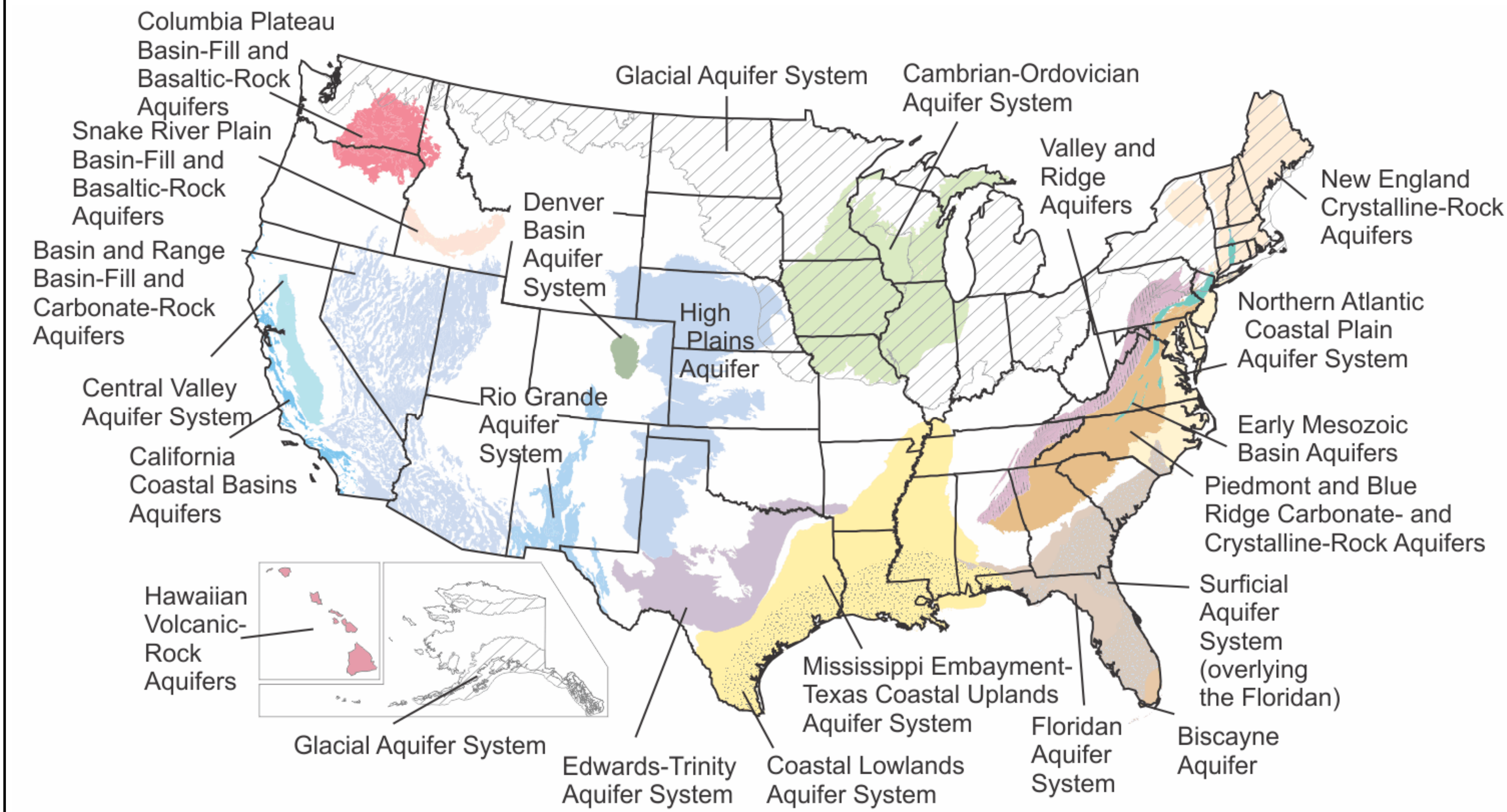
Aquifers

Date: 4/16/2018	Project # NA:	**Figure 4**



https://water.usgs.gov/nawqa/studies/praq/

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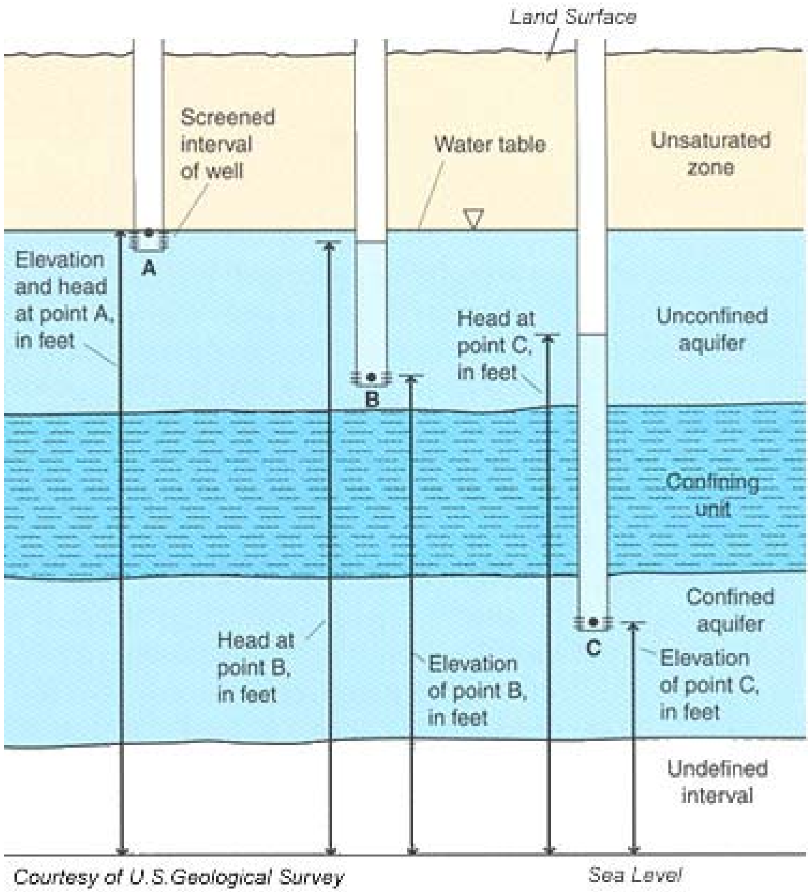
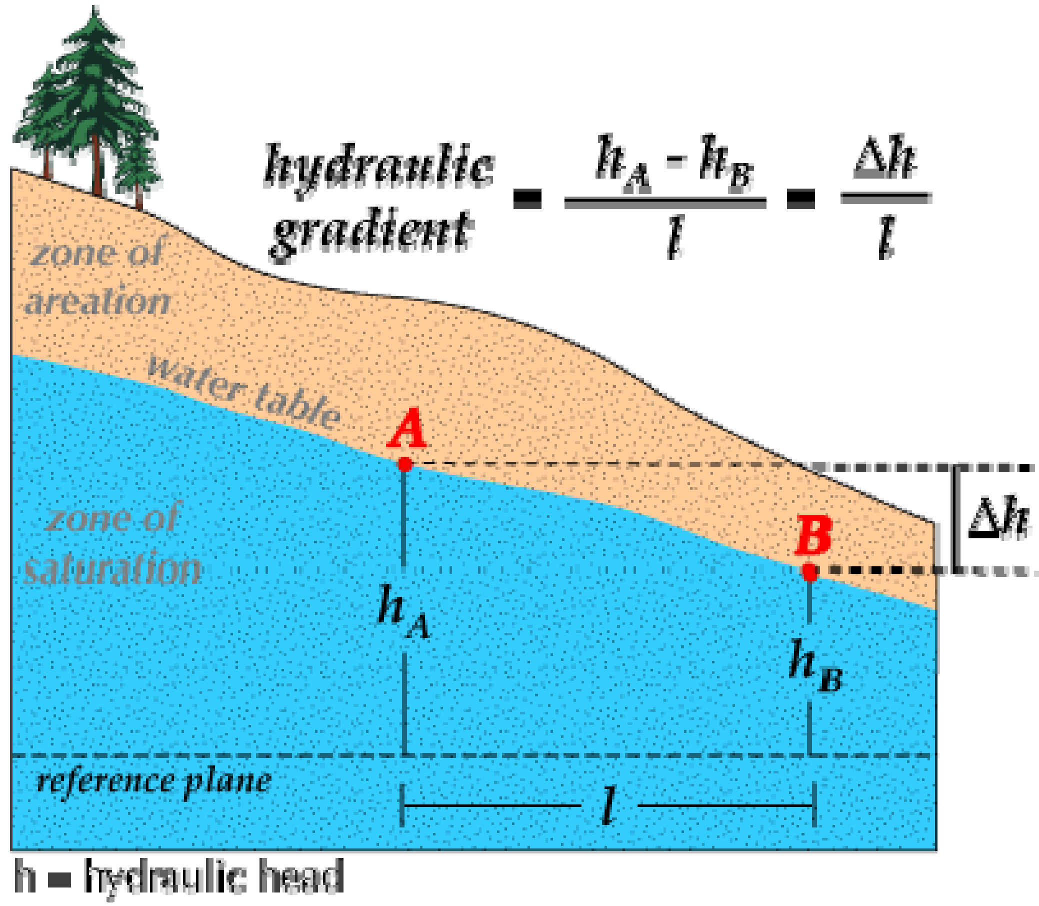
Principal Aquifers in the USA

Date: 4/16/2018	Project # NA:	**Figure 5**





United States Geological Survey (USGS). (1999). Sustainability of Ground-Water Resources. Circular 1186.
http://pubs.usgs.gov/circ/circ1186/images/fig07.gif
https://s-media-cache-ak0.pinimg.com/originals/71/42/9c/71429c97a14e30ee91d20995d1f506c2.jpg

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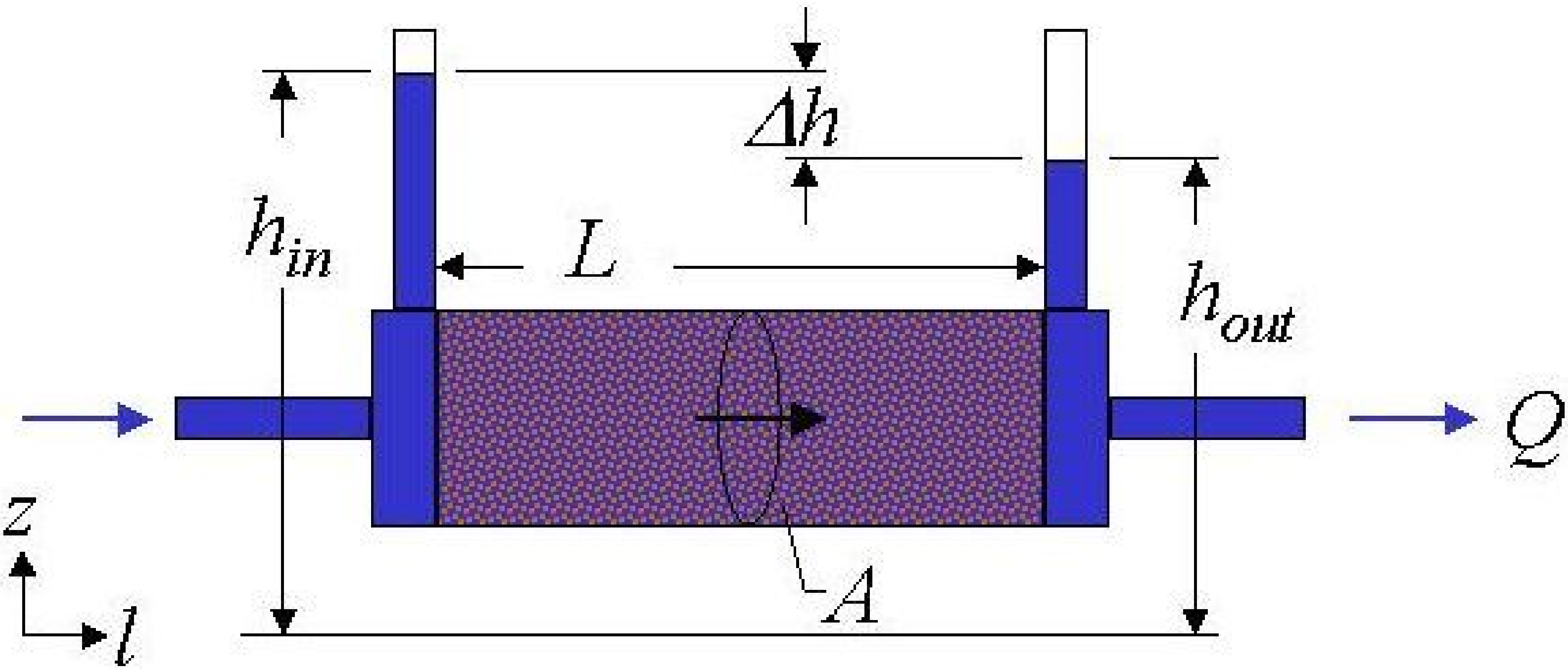
Hydraulic Head and Gradient

Date: 4/16/2018	Project # NA:	**Figure 6**



$$Q = K*(\Delta h/L)*A$$

https://bae.okstate.edu/faculty-sites/Darcy/LaLoi/Basics.htm

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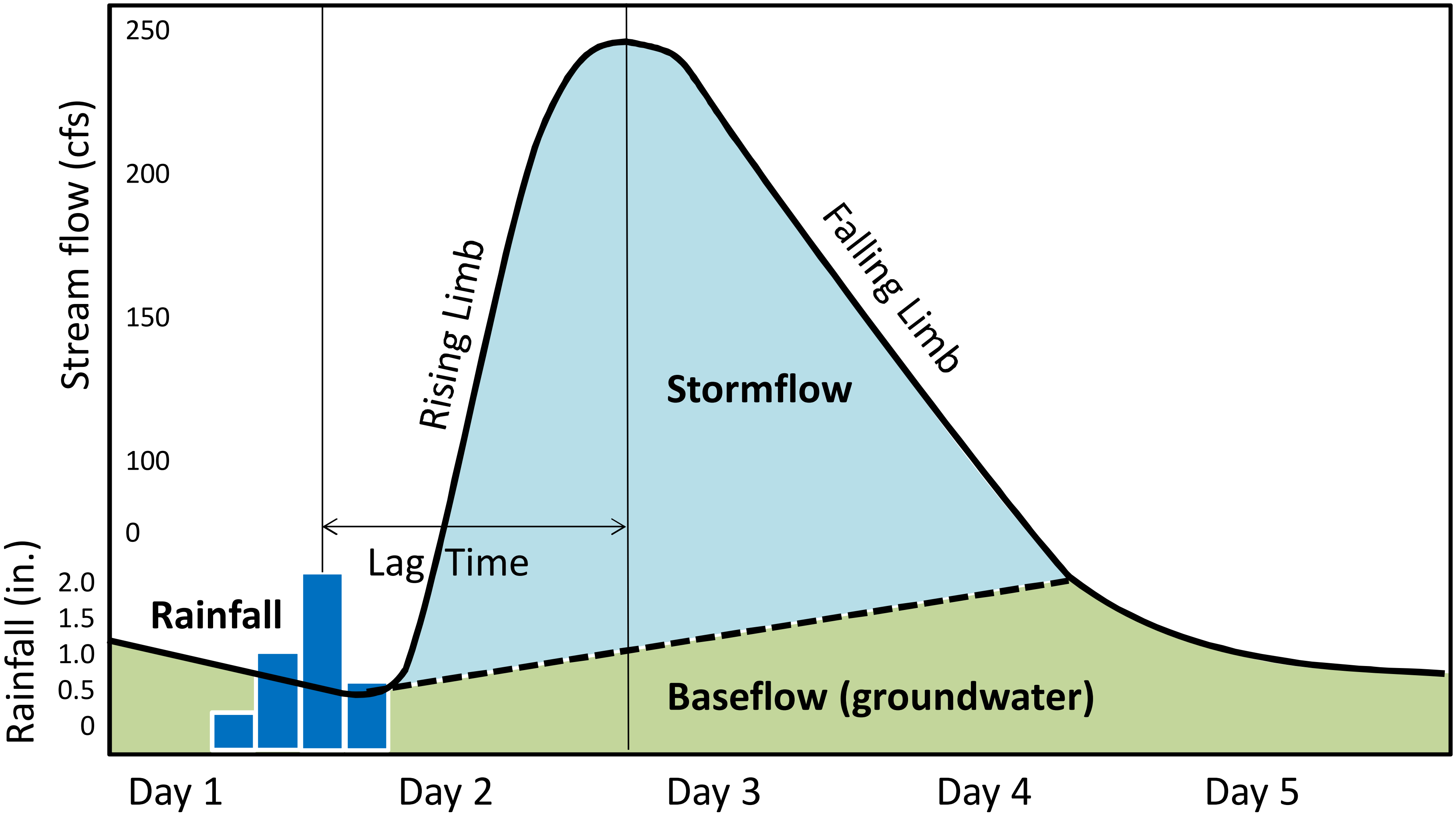
Darcy's Law

Date: 4/16/2018	Project # NA:	**Figure 7**



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Stream Hydrograph

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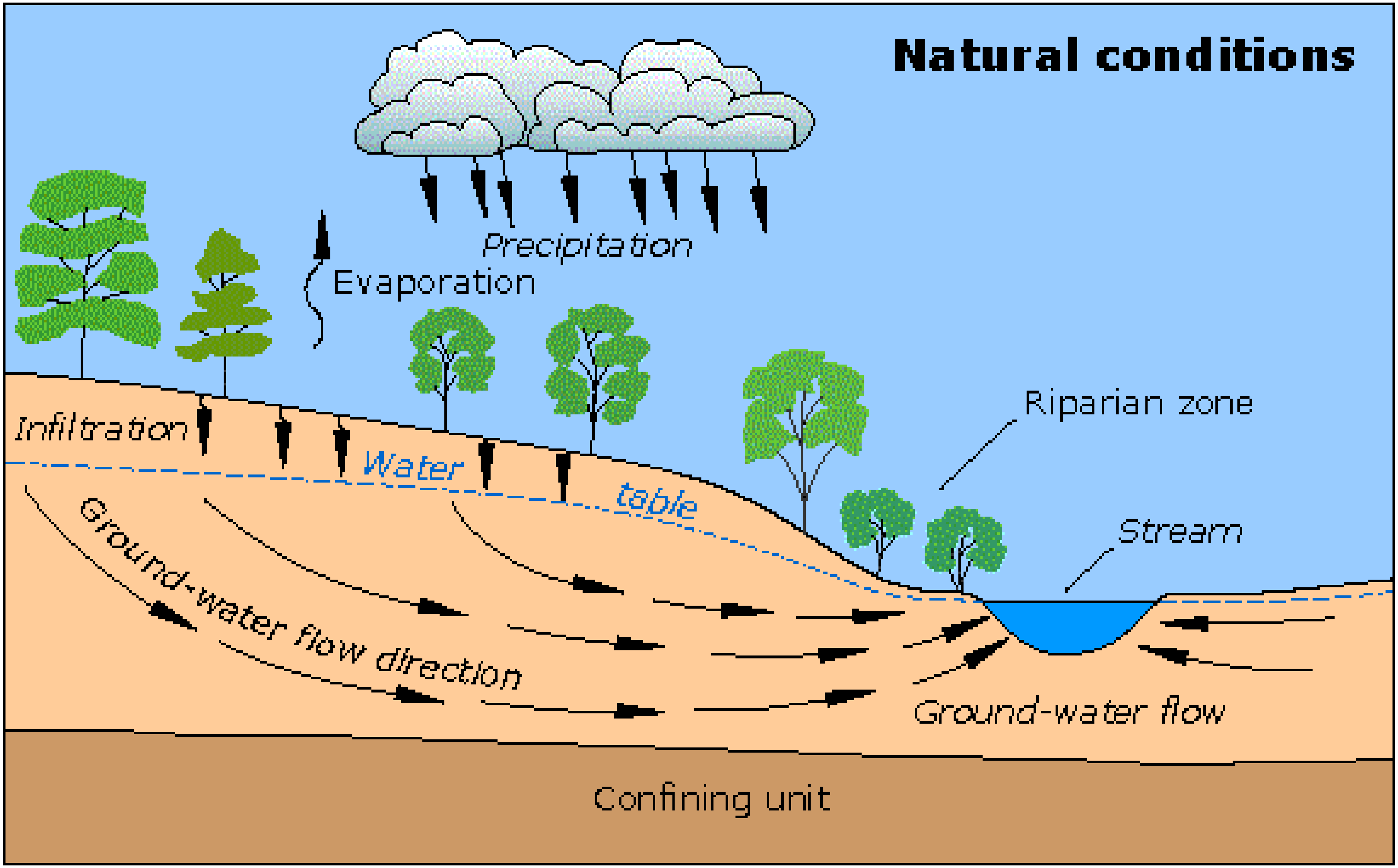

https://water.usgs.gov/edu/earthgwdecline.html

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Groundwater Flow to a Stream

Date: 4/16/2018	Project # NA:	**Figure 9**

Key

Density	CA MCL
Solubility	CA PHG
TCE Trichloroethene	
Vapor Pressure	Log K_{OC}
Henrys Law	Mol. Wt.

Classification Key

- I Chlorinated Hydrocarbons
- II Oxygenates
- III Petroleum Hydrocarbons
- IV Fluorinated Hydrocarbons
- V Chlorinated Aromatic Hydrocarbons
- VI Pesticides
- VII Poly-Chlorinated Biphenyls (PCBs)
- VIII Non-Chlorinated Phenols
- IX Poly-Aromatic Hydrocarbons (PAHs)
- X Other
- XI Metals
- XII Ionic Species

Volatile

I

Symbol	Name	Density	Solubility	CA MCL	CA PHG	Vapor Pressure	Henrys Law	Log K_{OC}	Mol. Wt.
PCE	Tetrachloroethene	1.62	2E05	5	0.06	18.4	0.76	2.19	165.83
111TCA	1,1,1-Trichloroethane	1.32	1.33E06	200	1,000	124	0.72	2.04	133.40
TCE	Trichloroethene	1.46	1.1E06	5	1.7	72.0	0.43	1.97	131.39
112TCA	1,1,2-Trichloroethane	1.44	4.42E06	5	0.3	25.2	0.038	1.70	133.40
PCA	1,1,2,2-Tetrachloroethane	1.59	2.97E06	1	0.1	5.17	0.015	1.89	167.85
11DCE	1,1-Dichloroethene	1.21	2.4E06	6	10	591	1.06	1.81	96.94
11DCA	1,1-Dichloroethane	1.20	5.5E06	5	3	228	0.24	1.50	98.96
CT	Carbon Tetrachloride	1.59	8.05E05	0.5	0.1	112	1.20	2.44	153.82
c12DCE	cis-1,2-Dichloroethene	1.28	4.93E06	6	100	175	0.19	1.46	96.94
12DCA	1,2-Dichloroethane	1.25	8.7E06	0.5	0.4	81.3	0.053	1.24	98.96
MC	Methylene Chloride	1.33	1.54E07	5	5	455	0.09	1.07	84.93
T12DCE	trans-1,2-Dichloroethene	1.26	6.3E06	10	60	352	0.39	100.001	96.94
13DCP	1,3-Dichloropropane	1.22	2.16E06	NS	NS	19.26	0.055	2.09	110.97
CF	Chloroform	1.48	7.92E06	80	0.8	198	0.15	1.67	119.38
VC	Vinyl Chloride	0.91	2.76E06	0.5	0.05	2,800	3.49	1.04	62.5
12DCP	1,2-Dichloropropane	1.16	2.8E06	5	0.5	50	0.12	1.77	112.99
123TCP	1,2,3-Trichloropropane	1.38	1.9E06	0.005	0.0007	3.7	0.016	2.59	147.43

II

Symbol	Name	Density	Solubility	CA MCL	CA PHG	Vapor Pressure	Henrys Law	Log K_{OC}	Mol. Wt.
MTBE	Methyl Tert-Butyl Ether	0.74	4.8E07	13	13	249	0.024	1.15	88.15
TBA	Tert-Butyl Alcohol	0.78	Miscible	12 (AL)	NS	31.42	0.003	0.62	74.12
DIPE	Diisopropyl Ether	0.73	2.67E06	NS	NS	77.56	0.16	1.81	102.18
TAME	Tert-Amyl Methyl Ether	0.76	4.29E06	5 (S)	13	99.72	0.13	1.62	102.18
ETBE	Ethyl Tert-Butyl Ether	0.74	5.03E06	5 (S)	13	89.96	0.10	1.57	102.18

III

Symbol	Name	Density	Solubility	CA MCL	CA PHG	Vapor Pressure	Henrys Law	Log K_{OC}	Mol. Wt.
BNZ	Benzene	0.88	1.8E06	1	0.15	95	0.23	1.82	78.11
TOL	Toluene	0.87	5.3E05	150	150	28.2	0.28	2.15	92.14
EBNZ	Ethylbenzene	0.87	1.7E05	300	300	9.6	0.33	2.31	106.17
XYL	o,m,p-Xylene	0.88	1.8E05	1,750	1,800	6.75	0.00074	2.11	106.17

IV

Symbol	Name	Density	Solubility	CA MCL	CA PHG	Vapor Pressure	Henrys Law	Log K_{OC}	Mol. Wt.
F11	Trichlorofluoromethane	1.49	1.1E06	150	170	687	4.03	2.13	137.37
F12	Dichlorodifluoromethane	1.31	2.8E05	1,000 (NL)	NS	4,000	16.67	2.11	120.91
F113	Trichlorotrifluoroethane	1.56	2E05	1,200	4,000	360	22.03	3.11	187.38

V

Symbol	Name	Density	Solubility	CA MCL	CA PHG	Vapor Pressure	Henrys Law	Log K_{OC}	Mol. Wt.
CBENZ	Chlorobenzene	1.11	5.02E05	70	200	12.1	0.18	2.33	100.001
12DCB	1,2-Dichlorobenzene	1.30	1.5E05	600	600	1.36	0.087	2.84	147.00
14DCB	1,4-Dichlorobenzene	1.25	7.38E01	5	6	1.06	0.12	2.81	147.00

Semi-Volatile

VI

Symbol	Name	Density	Solubility	CA MCL	CA PHG	Vapor Pressure	Henrys Law	Log K_{OC}	Mol. Wt.
MTLCL	Metolachlor	1.12	5.3E05	NS	NS	1.67E-11	4.13E-07	2.08	283.8
PRMTN	Prometon	1.09	7.2E05	NS	NS	7.7E-06	1.3E-07	2.17	225.3
ATRZN	Atrazine	1.23	3.5E04	1	0.15	2.9E-10	1.2E-07	2	215.68
DDD	Dichlorodiphenyl Dichloroethane	1.385	9E01	NS	NS	8.7E-07	1.7E-04	5.38	320.04
EDB	Ethylene Dibromide	2.18	4.32E06	0.05	0.01	11	0.029	1.73	187.86
CLRDN	Chlordane	1.60	5.6E01	0.1	0.03	1.0E-05	0.002	5.08	409.78
GLYPT	Glyphosate	1.71	1.05E07	NS	NS	97.5	6.6E-19	1.4E03	168.07
DDE	Dichlorodiphenyl Dichloroethene	1.36	6.5E01	NS	NS	5.7E-06	8.7E-04	5.04	319.03
DBCP	1,2-Dibromo-3-Chloropropane	2.08	1E06	0.2	0.0017	0.76	8.3E-03	2.23	236.33
DLDRN	Dieldrin	1.75	1.95E02	NS	NS	9.9E-07	1.1E-04	4.33	380.91
SMZN	Simazine	1.3	5E03	4	4	6.07	1.30E-08	2.11	201.66
DDT	Dichlorodiphenyl Trichloroethane	0.99	3.1	NS	NS	3.9E-07	0.002	5.14	354.49

VII

Symbol	Name	Density	Solubility	CA MCL	CA PHG	Vapor Pressure	Henrys Law	Log K_{OC}	Mol. Wt.
A1242	Aroclor-1242	1.26	4.5E02	0.5	0.09	4.06E-03	No Data	No Data	266.5
A1254	Aroclor-1254	1.54	1.2E01	0.5	0.09	7.71E-05	2.0E-03	No Data	328
A1260	Aroclor-1260	1.62	2.7	0.5	0.09	4.05E-05	4.6E-03	No Data	357.7

VIII

Symbol	Name	Density	Solubility	CA MCL	CA PHG	Vapor Pressure	Henrys Law	Log K_{OC}	Mol. Wt.
PCP	Pentachlorophenol	1.98	2E05	1	0.3	1.1E-04	1E-06	3.54	266.34
PHNL	Phenol	1.07	8.7E07	NS	NS	0.46	2.47E-05	1.24	94.11
CRSL	o,m,p-Cresol	1.03	2.3E07	NS	NS	0.14	3.62E-05	1.94	108.14
DMP	2,4-Dimethylphenol	1.01	6.2E06	NS	NS	0.13	8.31E-05	2.07	122.17
DNP	2,4-Dinitrophenol	1.68	5.8E06	NS	NS	1.14E-04	2.01E-07	-2.0	184.11

IX

Symbol	Name	Density	Solubility	CA MCL	CA PHG	Vapor Pressure	Henrys Law	Log K_{OC}	Mol. Wt.
NAP	Naphthalene	1.14	3.14E04	170 (AL)	---	0.09	0.02	3.19	128.17
CRYSN	Chrysene	1.27	2.0E-03	NS	NS	7.8E-09	5.0E-05	5.49	228.29
BNZAN	Benzo(a)anthracene	1.19	1E-02	NS	NS	1.54E-07	0.00014	5.55	228.29
BNZPY	Benzo(a)pyrene	1.24	1.6E-03	0.2	0.007	4.89E-09	4.70E-05	5.98	252.31
BNZBFL	Benzo(b)fluoranthene	1.29	1.5E-03	NS	NS	8.06E-08	5.0E-04	6.08	252.32
BNZKFL	Benzo(k)fluoranthene	1.29	5.0E-04	NS	NS	9.59E-11	4.4E-07	6.09	252.32

X

Symbol	Name	Density	Solubility	CA MCL	CA PHG	Vapor Pressure	Henrys Law	Log K_{OC}	Mol. Wt.
MEK	Methyl Ethyl Ketone	0.80	2.4E08	NS	NS	91	0.0012	0.28	72.11
NDMA	N-Nitrosodimethylamine	1.01	Miscible	0.01 (NL)	0.003	5.37	2.2E-05	0.56	74.08
14DIOX	1,4-Dioxane	1.49	1.1E06	1 (NL)	NS	38	2.0E-04	-0.27	88.11

XI

Symbol	Name	Density	Solubility	CA MCL	CA PHG	Vapor Pressure	Henrys Law	Log K_{OC}	Mol. Wt.
As	Arsenic as Arsenic Pentoxide	4.32	2.3E09	10	0.004	0	0	1.39	229.84
Cd	Cadmium as Cadmium Chloride	4.05	Soluble	5	0.04	0	0	1.18	183.32
Pb	Lead as Lead Acetate	3.25	4.43E08	15	0.2	0	0	0.73	325.3
Se	Selenium as Hydrogen Selenide	2.12	5.7E09	50	30	0	0	0.34	78.96
Cu	Copper as Copper Sulfate	3.6	3.2E8	1,300	300	0	0	1.60	159.61
Tl	Thallium as Thallium Chloride	7.00	2.9E06	2	0.1	0	0	1.64	239.84
Hg	Mercury	13.53	3E01	2	1.2	0.0013	0.474	1.72	200.59
Be	Beryllium as Beryllium Chloride	1.85	Soluble	4	1	0	0	1.36	79.92

XII

Symbol	Name	Density	Solubility	CA MCL	CA PHG	Vapor Pressure	Henrys Law	Log K_{OC}	Mol. Wt.
ClO4	Perchlorate (as Ammonium Perchlorate)	1.95	2.49E08	6	6	V. Low	0	-0.5	117.49
CN	Cyanide (as HCN)	0.68	Miscible	150	150	13.8	No Data	0.99	27.03
NO3	Nitrate (as NO_3)	2.11	3.2E08 (as NO_3)	45,000	45,000	No Data	0	-2	62.00
Cr(VI)	Hexavalent Chromium as H_2CrO_4	1.67	1E09	50	0.02	0	0	1.15	118

Notes and Units

- MCL - Maximum Contaminant Level
- PHG - Public Health Goal
- NL - Notification Level
- AL - Action Level
- NS - No Standard
- NA - Not Applicable
- S - Secondary MCL

- MCL/PHG - ug/L
- Density - g/cm³
- Solubility - ug/L
- Vapor Pressure - mmHg (20-25 °C)
- Henry's Law - Unitless (20 °C)
- Log K_{OC} - mL/g
- Mol. Weight - g/mole

Sources

Agency of Toxic Substances and Disease Registry (ATSDR). Toxicological Profiles. http://www.atsdr.cdc.gov/toxprofiles/index.asp

Kerle, E.A., J.J. Jenkins, and P.A. Vogue. (2007). Understanding Pesticide Persistence and Mobility for Groundwater and Surface Water Protection. EM 8561-E. Oregon State University

Mackay, D., W.Y. Shiu, K. Ma, and S.C. Lee. Illustrated Handbook of Physical-Chemical Properties and Environmental Fate for Organic Chemicals. Vol. I-IV., Second Edition. CRC Press. 2006.

Montgomery, J.H. (2007). Groundwater Chemicals Desk Reference Fourth Edition. April.

Pesticides Property Database. Agriculture & Environment Research Unit, University of Hertfordshire. http://sitem.herts.ac.uk/aeru/footprint/index2.htm

United States Environmental Protection Agency (USEPA). (1996). Soil Screening Guidance: Technical Background Document. EPA/540/R95/128. May.

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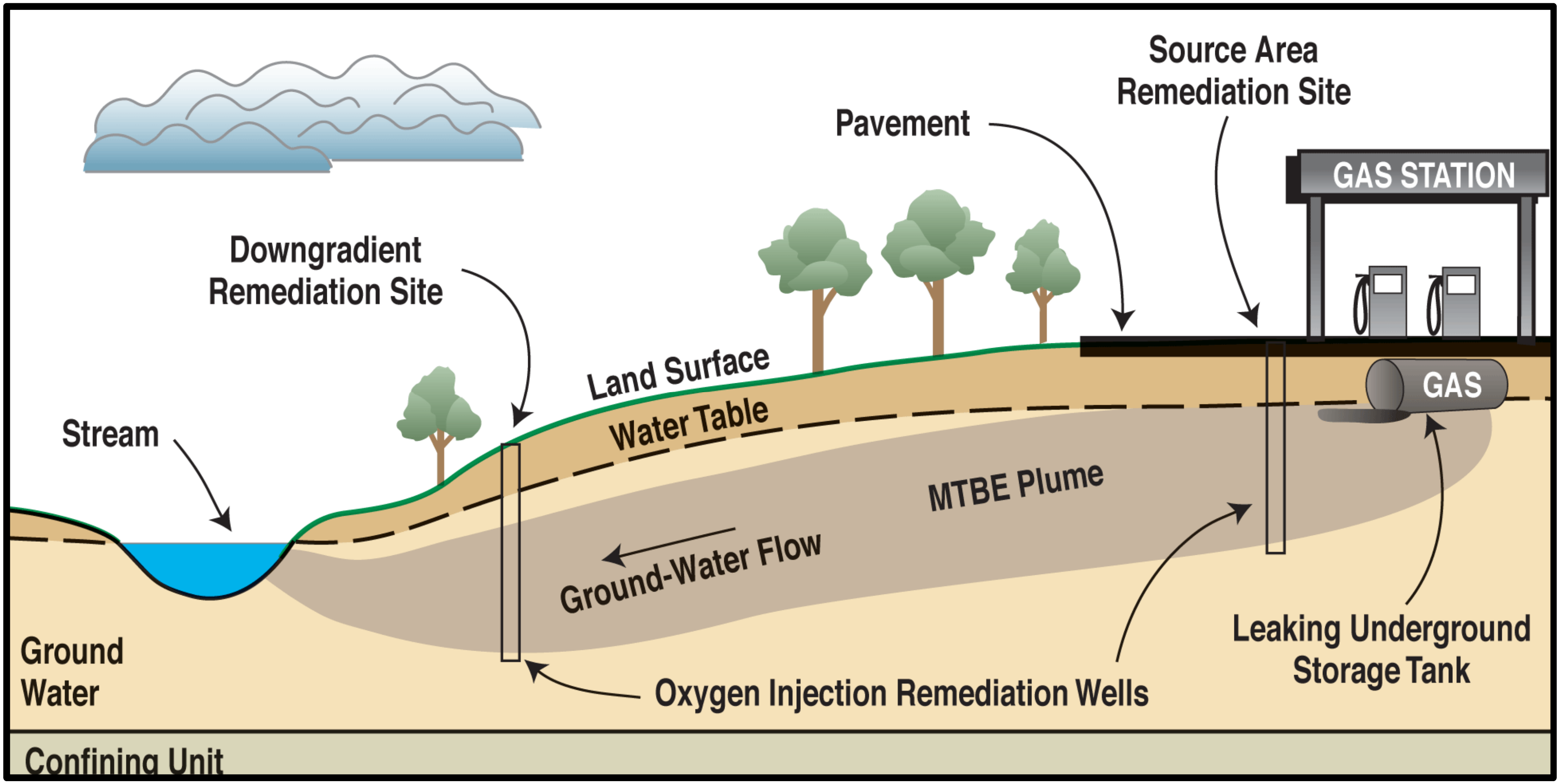
Periodic Table of Groundwater Contaminants

http://www.aquilogic.com/COCs.php

Date: 4/16/2018 | Project # NA: | **Figure 10**



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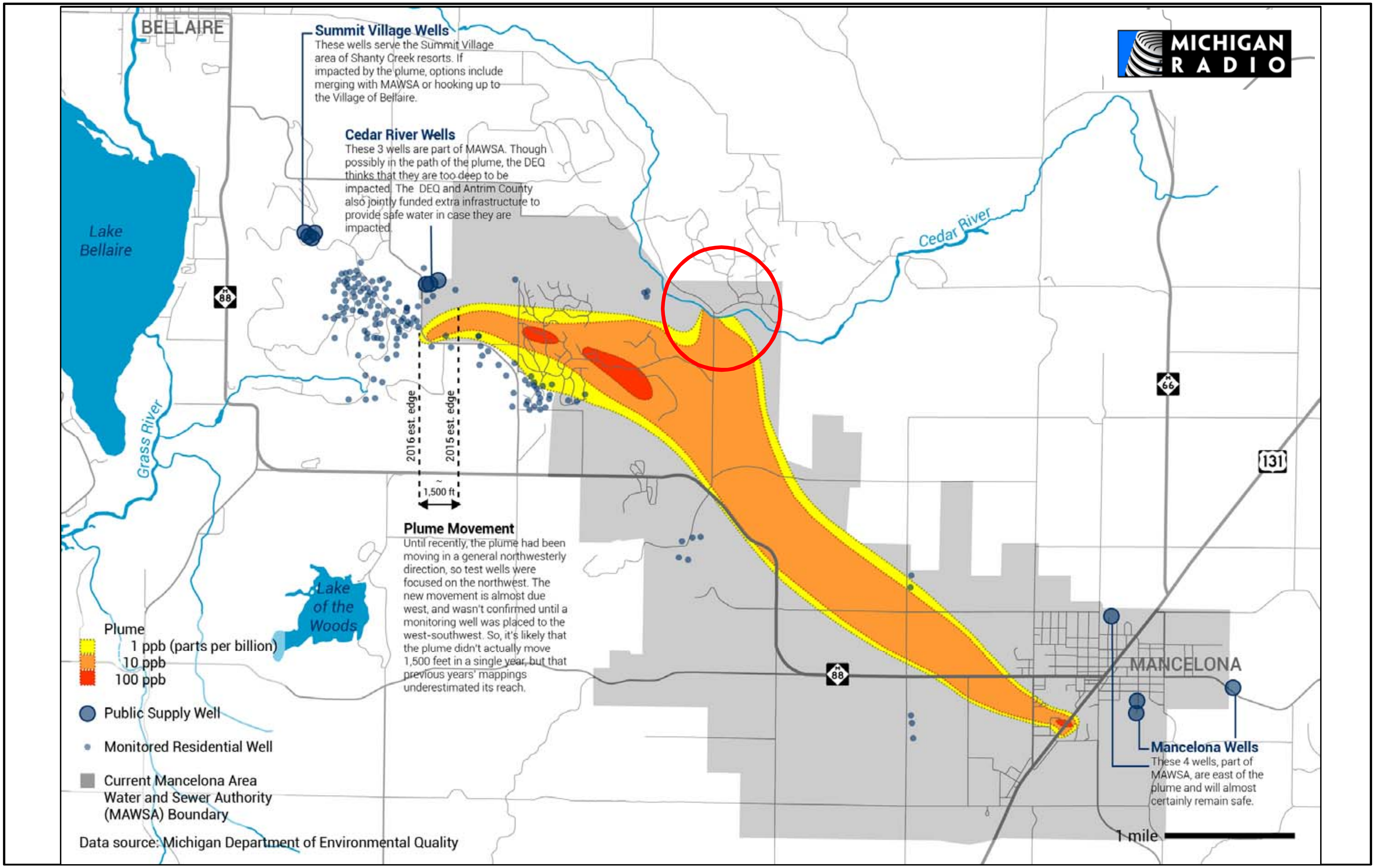
Groundwater Plumes

https://toxics.usgs.gov/highlights/o2_biodeg_lessons.html

Date: 4/16/2018	Project # NA:	**Figure 11**



http://michiganradio.org/post/northern-michigan-community-tries-stay-ahead-massive-contaminated-plume

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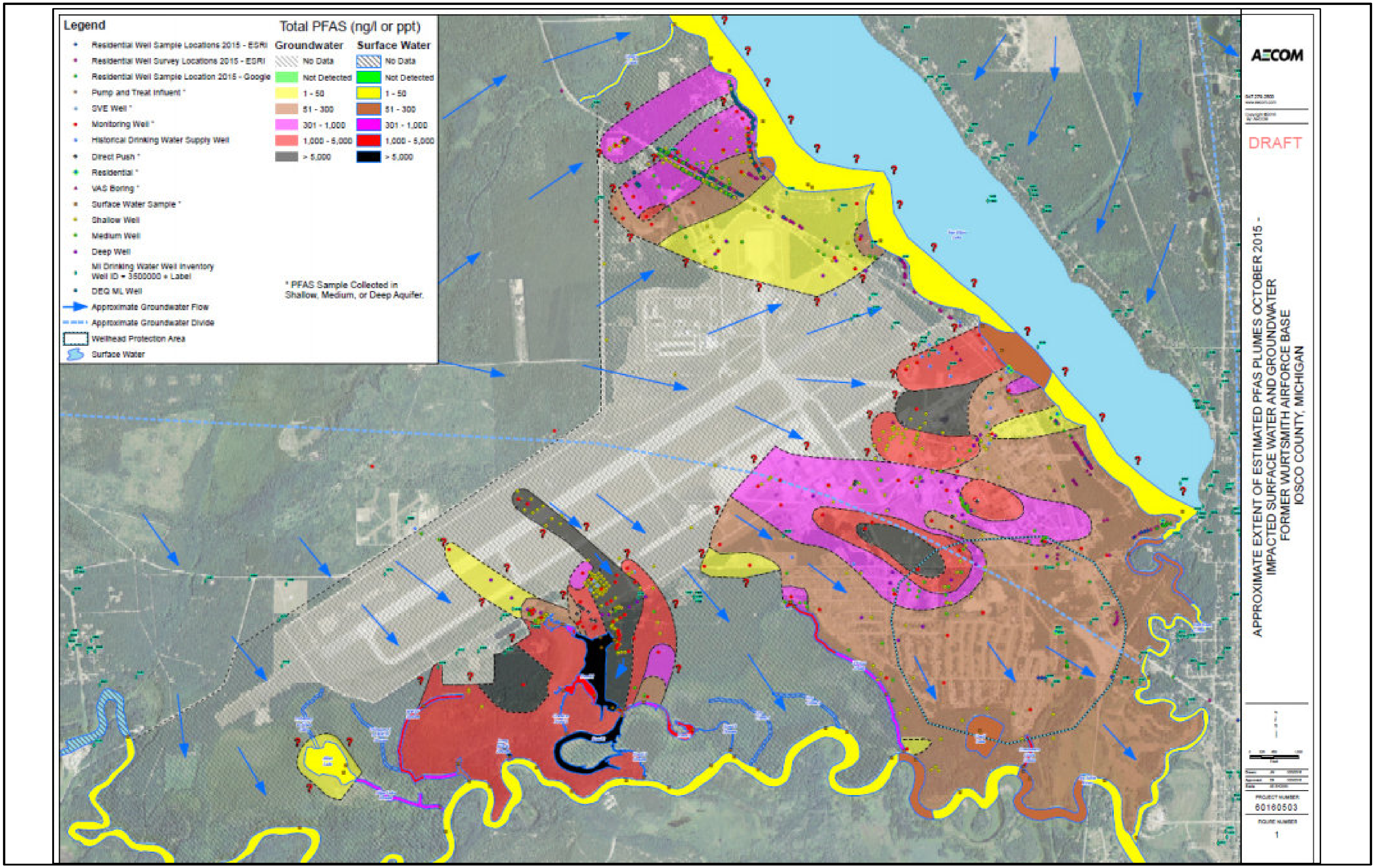
TCE Discharging to a River

Date: 4/16/2018	Project # NA:	Figure 12



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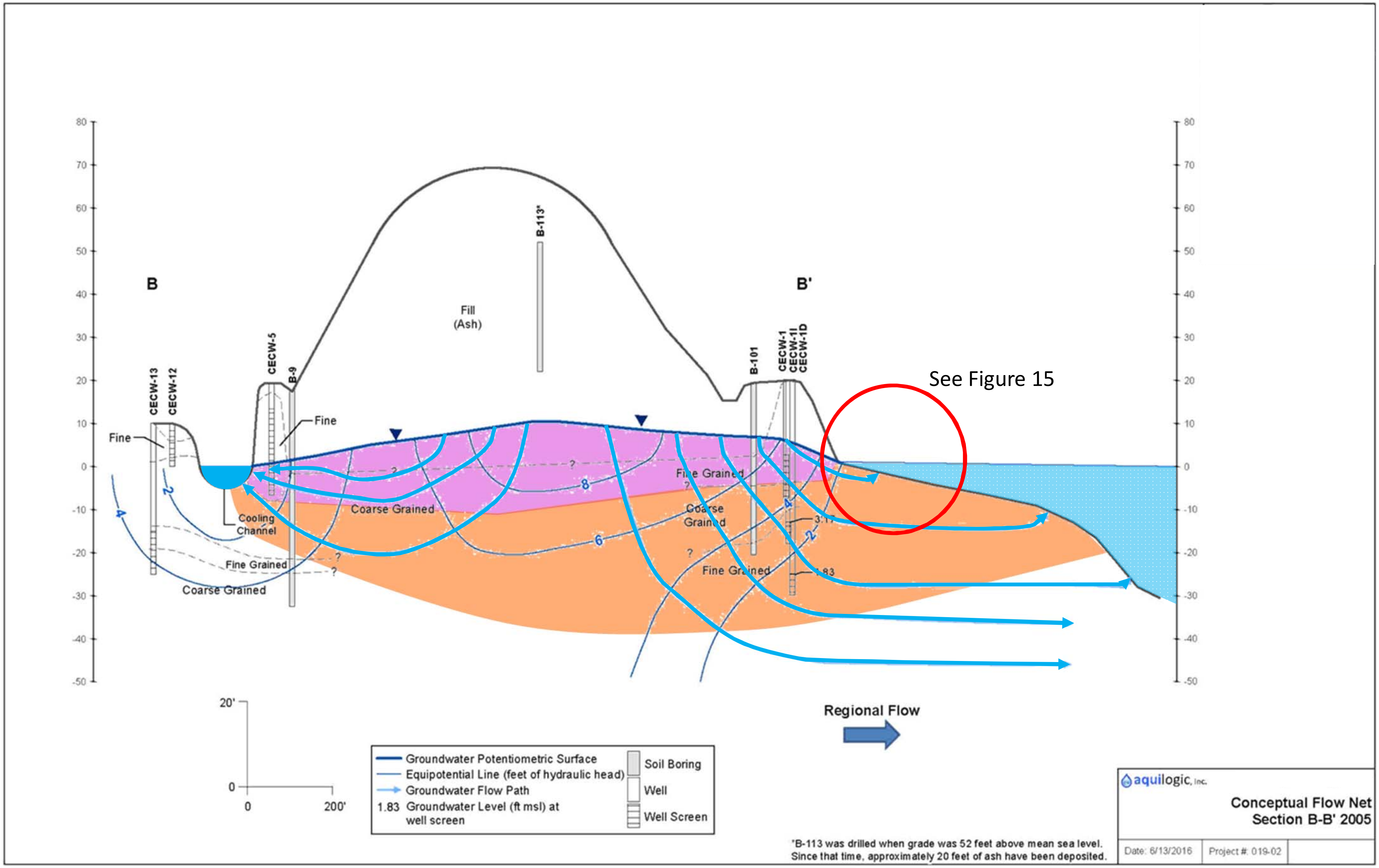
PFCs Discharging to Streams and a Lake

Date: 4/16/2018	Project # NA:	**Figure 13**

http://www.mlive.com/news/index.ssf/2016/06/water_now_testing_above_toxic.html



Coal ash waste in contact with groundwater

Contaminant plume

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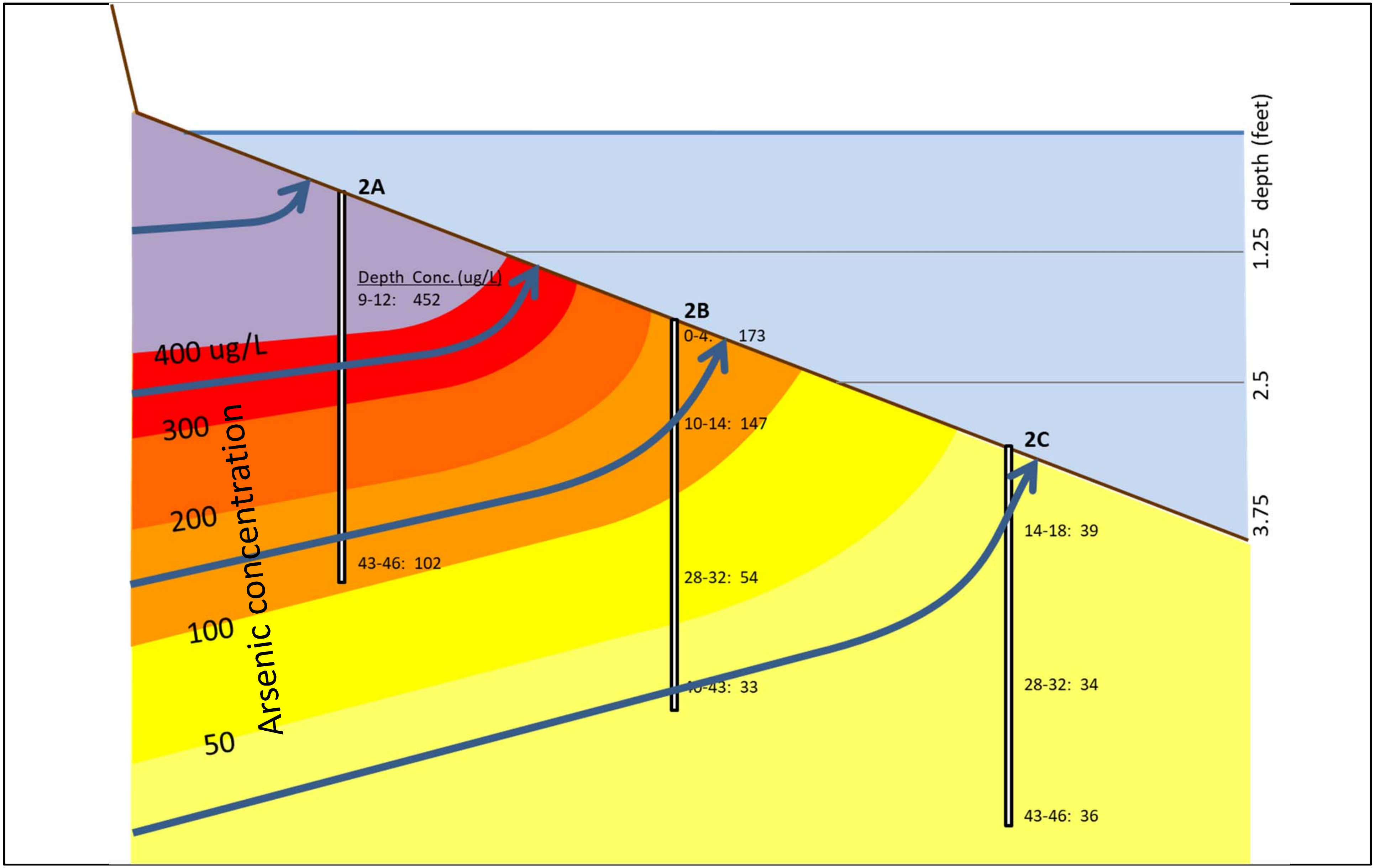
Arsenic Discharge to Surface Waters

Date: 4/16/2018	Project # NA:	**Figure 14**



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Arsenic Discharge to a River

Date: 4/16/2018	Project # NA:	**Figure 15**

Sticky piles of toxic PFAS foam plaguing Michigan lake Feb 4, 2018

"Residents near the former Wurtsmith Air Force Base in Oscoda Township have become increasingly concerned over the past year as toxic fluorochemicals leaching through the groundwater have generated white foam that's washing ashore on public beaches and private waterfronts around the picturesque Van Etten Lake."

http://www.mlive.com/news/index.ssf/2018/02/wurtsmith_pfas_foam_michigan.html

Firefighting foam used by unit of Johnson Controls poses toxic threat to Green Bay

March 19, 2018

"An underground plume of contamination from a firefighting training facility in Marinette has spread from the site and could be seeping into Lake Michigan's Green Bay, a little more than a mile away."

https://www.jsonline.com/story/news/politics/2018/03/19/firefighting-foam-used-unit-johnson-controls-poses-toxic-threat-green-bay/427678002/

Contaminated water open house draws crowd in Fairbanks Mar 14, 2018

"Understanding how the contamination plume interacts with the Chena River, and subsequently the Tanana River, is a major unknown…"

http://www.newsminer.com/news/local_news/contaminated-water-open-house-draws-crowd-in-fairbanks/article_f90bb8da-2760-11e8-a68e-534c1e36749f.html

Radioactive Waste Still Flooding Columbia River, EPA Says June 8, 2017

"Groundwater contaminated with radioactive waste from the decommissioned Hanford nuclear facility in Washington state is still "flowing freely" into the Columbia River, a program manager with the U.S. Environmental Protection Agency said at a meeting of the Hanford Advisory Board."

https://www.courthousenews.com/radioactive-waste-still-flooding-columbia-river-epa-says/

Extremely high PFAS levels found at Wolverine tannery site November 9, 2017

"Extremely high levels of toxic fluorochemicals once used to waterproof shoe leather are in groundwater at Wolverine World Wide's former tannery property and lower levels have been found in the Rogue River north and south of Rockford."

http://www.mlive.com/news/grand-rapids/index.ssf/2017/11/extremely_high_pfas_levels_fou.html

Environmental groups continue fight against Kinder Morgan after 4th Circuit revives lawsuit

Apr 13, 2018

""Pumping air into the wells and then bubbling the stream is not doing the job," Robbins said. "Unless effective additional action is taken, this spill will be polluting the river system for years to come."

https://greenvillejournal.com/2018/04/13/environmental-groups-continue-fight-against-kinder-morgan-after-fourth-circuit-revives-federal-lawsuit/

Pollution plumes stopped by drought but how much longer for cleanup? Apr 22, 2017

"It was a 300-acre plume of highly volatile gasoline, diesel and some crude oil that had leaked onto the ground for so long it had reached depths of 200 feet in some places. And, as I said, it was moving toward the Kern River bed, Bakersfield's main recharge channel for the groundwater that we all rely on to live.."

http://www.bakersfield.com/columnists/lois-henry-pollution-plumes-stopped-by-drought-but-how-much/article_c912036c-a3b4-5f1d-87a2-0fc818910dcb.html

Colorado River at Risk May 27, 2007

"Arizona was not only worried about The Plume affecting the river water, which would be carried to Phoenix and Tucson, but about it traveling under the river and contaminating ground water in the river village of Topock, which, like Hinkley, uses well water for drinking."

https://lasvegassun.com/news/2007/may/27/colorado-river-at-risk/

City wants to ensure Coakley 'isn't poisoning anyone Apr 3, 2018

"Nearby Berry's Brook has high levels of PFAS in its surface water and DES officials have said it needs to be cleaned and warned against people eating fish caught in the brook."

http://www.seacoastonline.com/news/20180403/mayor-city-wants-to-ensure-coakley-isnt-poisoning-anyone11

Carcinogenic Chemical Spreads Beneath American Town Sept. 3, 2013

"The plume – now polluting 13 trillion gallons of groundwater – is advancing northwest at a rate of about 300 feet per year. It has reached the Cedar River, which flows to a chain of lakes that wash into Lake Michigan."

https://www.scientificamerican.com/article/carcinogenic-chemical-spreads-beneath-american-town/

PG&E Begins Pumping Toxic Groundwater Away from Colorado River Mar 8, 2004

"The MWD operates the Colorado River Aqueduct – a major source of Los Angeles' drinking water – and MWD officials say a plume of at least 108 million gallons of tainted water is on course to reach the river at a point 42 miles upstream from intakes for both the MWD's aqueduct and the Central Arizona Project – an agricultural and urban water delivery system."

https://www.wqpmag.com/pge-begins-pumping-toxic-groundwater-away-colorado-river

Oscoda toxic PFC groundwater plumes approaching Lake Huron

September 13, 2016

http://www.mlive.com/news/index.ssf/2016/09/oscoda_toxic_groundwater_plume.html

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Recent News Articles Describing Pollutant Discharge to Surface Waters

Date: 4/16/2018	Project #: NA	**Figure 16**

APPENDIX A: BIOGRAPHICAL SKETCH FOR ANTHONY BROWN