Salinity Network Workgroup

Groundwater Seawater Intrusion Index

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Development of an Index

Seawater Intrusion in Coastal Aquifers

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- Study goals were designed to develop a Groundwater Quality Index for Seawater Intrusion ($GQI_{(SWI)}$) specific to seawater intrusion that produces transformations for mapping the data. Pattern diagrams (e.g. Piper and Stiff) are traditionally used to characterize vulnerability to seawater intrusion but do not facilitate geospatial analyses. Modern needs are for an index with no limitation on the ability of spatial-temporal mapping of monitoring data.

- The Groundwater Quality Index for Seawater Intrusion ($GQI_{(SWI)}$), has the primary goal of the GIS-based index to rapidly aggregate chemical data into a quantifiable values that can be spatially and temporally mapped. Resulting maps provide a helpful and robust visual tool for scientists, researchers, management, policy makers and the public.

- To verify and test the reliability of the proposed Index $GQI_{(SWI)}$, water quality samples were obtained from worldwide coastal areas threatened by coastal seawater intrusion (Table 3). Florida is one of the areas included in the study.

GQI Sequential Equations to Final Index

- The Seawater Fraction Index ($f$sea) is approximated from the chloride concentrations in milliequivalents/L (m_{Cl}) shown below in Equation 1.

$$f_{\mathrm{sea}} = \frac{m_{\mathrm{Cl(sample)}} - m_{\mathrm{Cl(freshwater)}}}{m_{\mathrm{Cl(seawater)}} - m_{\mathrm{Cl(freshwater)}}}$$

- The GW Seawater Intrusion Index GQI $_{(piper\ mix)}$ is for simple mixing and the calculated number GQI($_{piper\ mix)}$ is the center horizontal line in Piper diagram. The GQI $_{(piper\ mix)}$ can range from 0, representing highly saline water (Domain II), to 100, representing highly fresh water (Domain I) and is derived in Equation 2.

$$\mathrm{GQI_{Piper(mix)}} = \left[\frac{(\mathrm{Ca^{2+}} + \mathrm{Mg^{2+}})}{\mathrm{Total\ \ cations}} + \frac{\left(\mathrm{HCO_3^-}\right)}{\mathrm{Total\ \ anions}}\right] \times 50 \quad (\mathrm{in\ \ meq/l})$$

- Further definition of the other domains in Figure 2 can be accomplished when GQI($_{piper\ mix)}$ is used with another index, GQI $_{(Piper(dom)}$ as in Equation 3.

$$\mathrm{GQI_{Piper(dom)}} = \left[\frac{(\mathrm{Na^{+}} + \mathrm{K^{+}})}{\mathrm{Total\ \ cations}} + \frac{\left(\mathrm{HCO_3^-}\right)}{\mathrm{Total\ \ anions}}\right] \times 50 \quad (\mathrm{in\ \ meq/l})$$

- Groundwater Quality Index for Seawater Intrusion (GQI$_{(SWI)}$) as in Equation 5.

$$\mathrm{GQI_{SWI}} = \frac{\mathrm{GQI_{Piper(mix)}} + \mathrm{GQI}_{f_{\mathrm{sea}}}}{2}$$

Seawater and Freshwater Hydrochemistry

Types of Groundwater Indicator Parameters

Freshwater, brackish water, and seawater etc. can be categorized by Typical Ranges of Cl, TDS, and EC (Table 1 below)

Class	Cl (meq/l)	TDS (ppm)	EC
Fresh Groundwater	<2.8	0-500	<700
Slightly Saline Groundwater	2.8 - 7.1	500 - 1500	700 - 2000
Moderately Saline Groundwater	7.1 - 14.1	1500 - 7000	2000 - 10,000
Highly Saline Groundwater	14.1 - 28.2	7000 - 15,000	10,000 - 25,000
Very Highly Saline Groundwater	28.2 - 82.2	15,000 - 35,000	25,000 - 45,000
Seawater	>282.2	>35,000	>45,000

*Adapted from Konikow and Reilly, 1999; Rhoades et al., 1992

Note: Values will be revised to agree with those typical for Florida

GW Use of Piper Diagram for Classification of Reaction Pathways

- Groundwater Quality Index for Seawater Intrusion ($GQI_{(SWI)}$) is derived by combining the **Seawater Fraction Index ($f$sea)** and the **Freshwater-Seawater Mixing Index ($GQI_{(piper\ mix)}$)** from the Piper diagram, showing a more representative performance over using either factor alone.
- ArcGIS has geoprocessing toolsets that can be used to assign characteristics to wells based on their locations and/or data. Results from multiple analyses, such as groundwater wells in a region, can be plotted on the same Piper diagram and then interpreted to identify the chemical characteristics, or hydrochemical facies, in defined domains (Back, 1961).
- Simple mixing of the two waters is denoted by the horizontal line across the center of the Piper diagram and numerically represented by **$GQI_{(piper\ mix)}$** as expressed in **Equation 2**.

Classification of Reaction Pathways for Waters and Seawater Intrusion

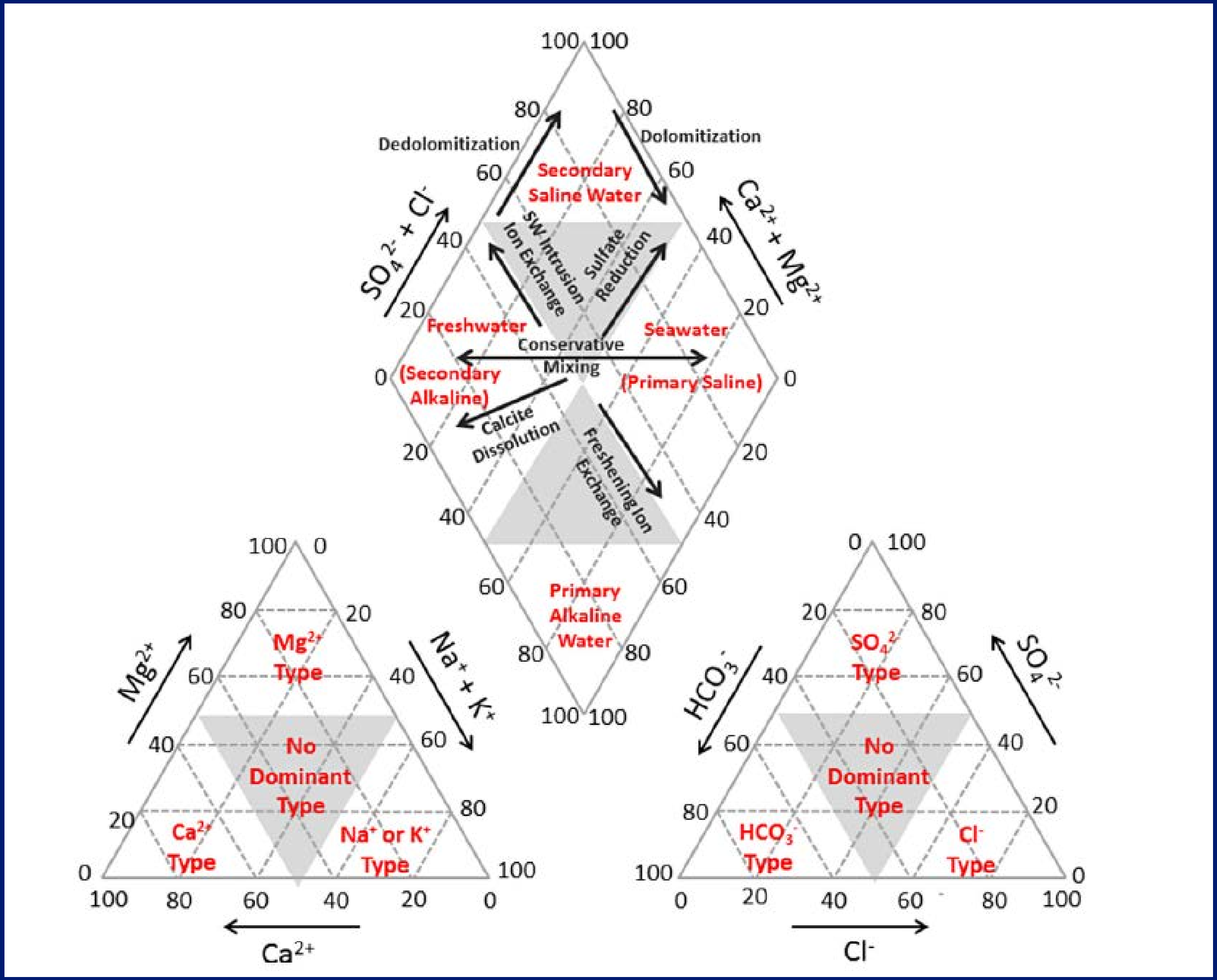


Fig. 1. Piper diagram illustrating general classifications of waters and seawater intrusion reaction pathways.

Adapted from Appelo and Postma, 2005; Hanshaw and Back, 1979; Singhal and Gupta, 2010; Panteleit et al., 2011

Compare Piper Diagram to Seawater Fraction

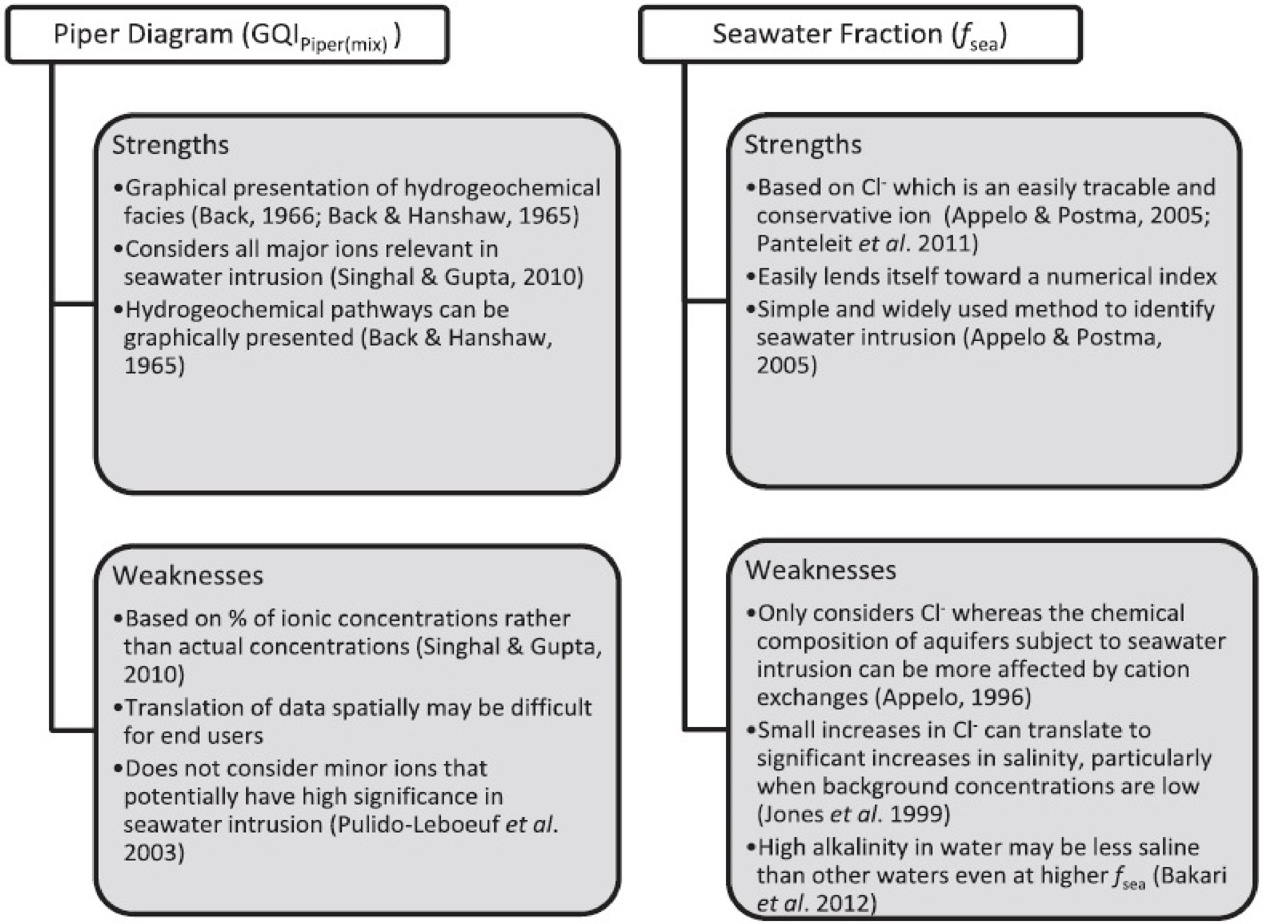
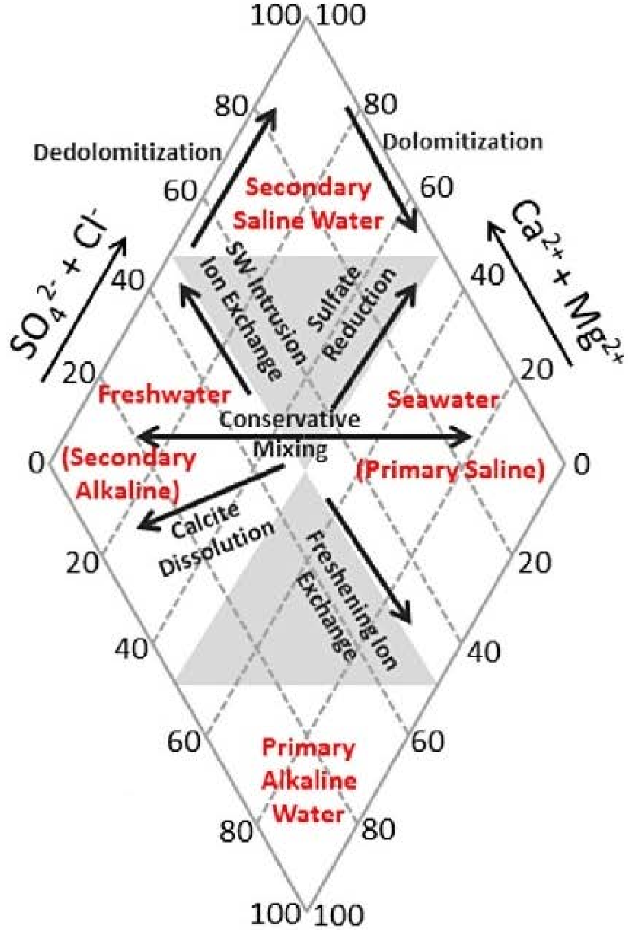


Fig. 4. Strengths and weaknesses of the Piper diagram and the seawater fraction (common tools to identify seawater intrusion).

Development of New Methodology

Piper Diagrams Values for Spatial Mapping



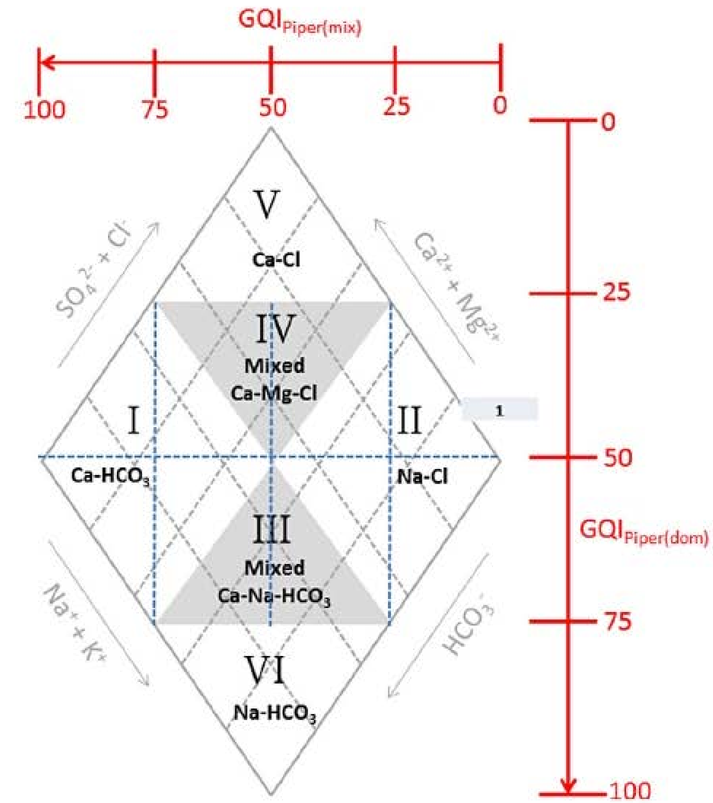


Fig. 2. Development of the $GQI_{Piper(mix)}$ and $GQI_{Piper(dom)}$ resultant domains.

Fig. 1. Piper diagram illustrating general classifications of waters and seawater intrusion reaction pathways.
Adapted from Appelo and Postma, 2005; Hanshaw and Back, 1979; Singhal and Gupta, 2010; Panteleit et al., 2011

Piper Diagram Methodology

Determining Hydrogeochemical Domains

- The six different domains are identified in the Piper diagram along with a crosswalk of numerical values for the Freshwater-Seawater Mixing Index ($GQI_{(piper\ mix)}$) and $GQI_{(piper\ dom)}$ Table 2. Freshwater is generally in Domain I, and saline water including seawater is in Domain II.

- The domains represent $CaHCO_3$, NaCl, mixed $CaNaHCO_3$, mixed CaMgCl, CaCl, and $NaHCO_3$ type waters as shown in Figure 2 and Table 2 below. Assigning domains are accomplished when $GQI_{(piper\ mix)}$ is used concurrently with another index, $GQI_{(piper\ dom)}$. Both are shown in Table 2 with the values for each domain.

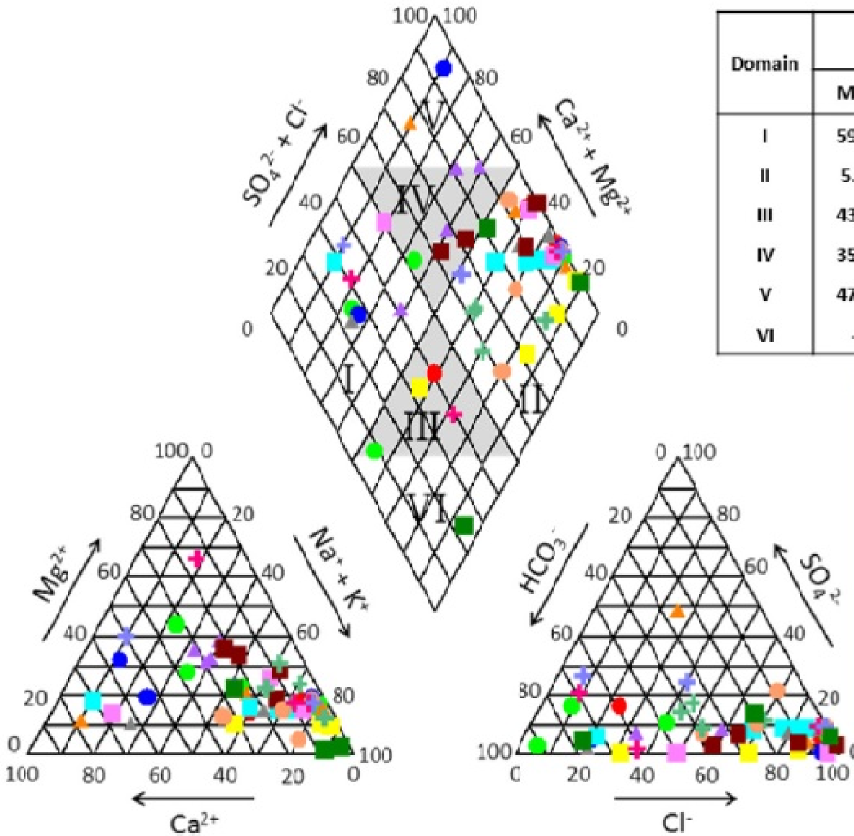
Table 2

$GQI_{Piper(mix)}$ and $GQI_{Piper(dom)}$ to determine hydrogeochemical domains.

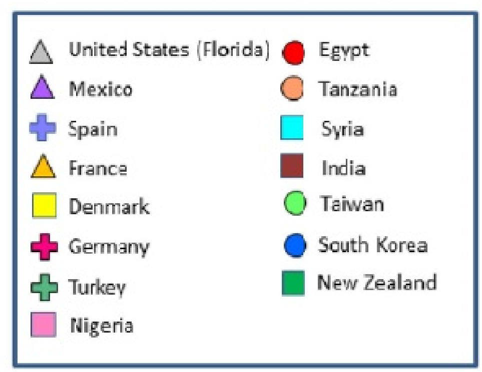
Domain	$GQI_{Piper(mix)}$	$GQI_{Piper(dom)}$
I	50–100	25–75
II	0–50	25–75
III	25–75	50–75
IV	25–75	25–50
V	25–75	0–25
VI	25–75	75–100

Worldwide Seawater Intrusion Studies

$GQI_{(piper\ mix)}$ - $GQI_{(piper\ dom)}$



Domain	$GQI_{Piper(mix)}$			$GQI_{Piper(dom)}$		
	Min	Max	Ave	Min	Max	Ave
I	59.9	80.2	73.7	38.7	51.5	46.5
II	5.1	37.7	19.0	31.1	59.7	42.1
III	43.9	67.6	54.2	60.4	72.7	65.6
IV	35.6	64.3	46.6	25.4	45.2	35.9
V	47.1	58.0	52.6	9.0	18.0	13.5
VI	-	-	41.0	-	-	86.2



Data used is in Table 3 includes Florida

Fig. 6. Piper diagram for worldwide studies and corresponding $GQI_{Piper(mix)}$ and $GQI_{Piper(dom)}$

Seawater Intrusion Index GQI$_{(SWI)}$

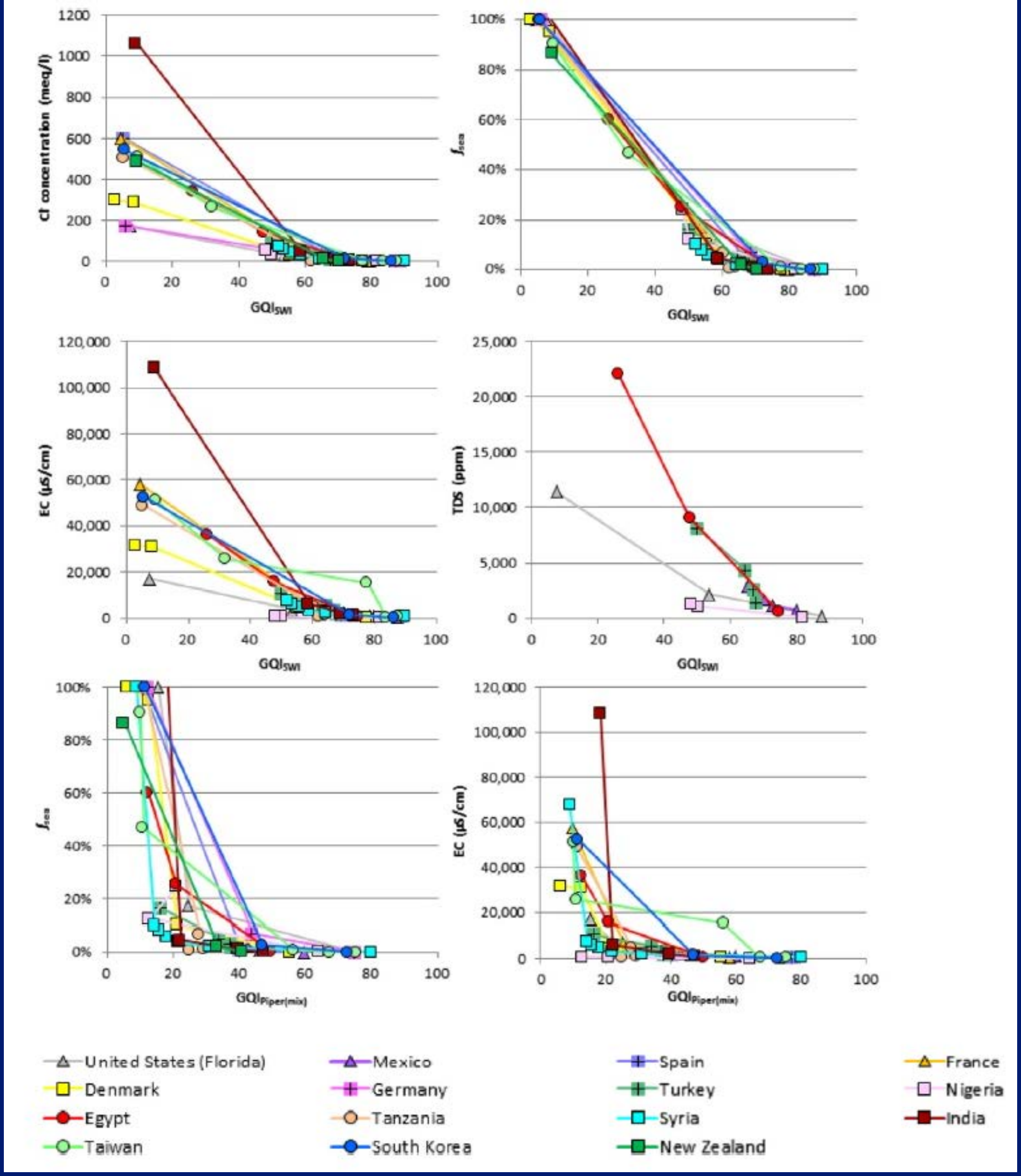
Worldwide Seawater Intrusion Studies for Index Verification

[redacted]

Country	Salinity source	Water type	f_{sea} (%)	TDS (ppm)	EC (μS/cm)	Hydrochemical analysis (meq/l)							Reference
						Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	Cl^{-}	SO_4^{2-}	HCO_3^{-}	
United States (Florida)	Atlantic Ocean	FGW	0.0	200	516	3.8	0.6	1.5	0.1	1.4	0.1	4.9	Price and Swart (2006)
		MGW	17	2150	3565	8.1	5.5	24.0	0.6	30.6	2.4	5.3	
		SW	100	11,460	17,136	21.9	35.2	143.7	4.5	171.2	15.4	5.7	
Mexico	Pacific Ocean	MGW	0.1	671	961	2.8	2.8	3.5	0.1	3.2	0.6	5.6	Cardona et al. (2004)
		MGW	1.0	1094	1570	4.3	4.9	6.0	0.1	8.6	1.1	4.7	
		MGW	2.2	1740	2477	8.4	9.1	8.5	0.2	16.0	3.1	4.5	
		MGW	4.8	2875	4118	9.8	16.1	16.9	0.3	31.2	4.9	4.5	
Spain	Mediterranean Sea	FGW	0.0	–	643	4.4	3.5	1.0	0.0	0.7	2.2	5.6	Pulido-Leboeuf (2004)
		MGW	1.0	–	1496	4.6	4.1	9.5	1.0	6.7	3.9	5.8	
		SW	100	–	–	24.2	111.4	511.4	2.0	600.0	61.6	2.6	
France	Mediterranean Sea	FGW	0.1	–	7,89	6.5	0.9	0.8	0.1	1.3	2.4	1.3	de Montety et al. (2008)
		MGW	10	–	7100	14.8	13.0	37.0	0.6	59.0	2.3	5.5	
		SGW	100	–	57,900	12.2	93.0	501.0	8.9	600.0	13.7	13.6	
Denmark	Isefjord Bay	FGW	0.0	–	494	1.0	0.3	1.7	0.1	1.7	0.0	3.5	Andersen et al. (2005)
		MGW	10	–	4580	1.6	3.5	29.3	1.0	32.6	0.1	12.8	
		SGW	95	–	30,800	7.8	26.3	237.9	5.3	286.6	3.6	42.3	
		SW	100	–	31,796	6.7	28.2	262.6	5.8	300.7	14.1	2.8	
Germany	North Sea	FGW	0.0	–	–	0.8	3.4	0.7	0.3	1.3	2.8	9.4	Panteleit et al. (2011)
		MGW	6.8	–	–	3.2	5.4	23.8	0.1	13.0	0.6	21.6	
		SW	100	–	–	10.0	32.6	143.5	3.4	173.5	18.0	3.9	
Turkey	Black Sea	MGW	1.9	1367	1940	3.3	4.4	12.7	–	11.0	1.8	7.8	Arslan (2013)
		MGW	3.2	2537	3490	2.9	11.6	23.5	–	17.8	6.5	13.9	
		MGW	5.0	4319	5490	2.9	13.8	42.6	–	28.1	8.7	26.4	
		SGW	16	8132	10,540	4.4	15.0	109.4	–	91.9	14.3	22.8	
Nigeria	Atlantic Ocean	FGW	0.2	79.5	48.3	1.0	0.2	0.3	0.0	0.6	0.0	0.6	Edet and Okereke (2001)
		MGW	12	1052	673	2.1	4.2	21.3	0.3	29.5	0.1	1.0	
		SGW	24	1250	800	7.0	13.1	31.5	0.8	58.1	0.0	2.0	
Egypt	Mediterranean Sea	FGW	0.3	560	717	1.8	1.3	4.5	0.2	1.8	1.2	4.5	Elewa et al. (2013)
		MGW	25	9081	15,908	38.4	22.5	95.6	2.0	142.9	7.8	5.2	
		SGW	60	22,067	36,467	25.8	67.3	287.1	3.7	339.8	35.9	2.7	
Tanzania	Indian Ocean	MGW	1.1	–	1319	1.8	0.6	9.8	0.2	6.4	0.8	4.6	Bakari et al. (2012)
		MGW	0.8	–	855	1.2	1.2	5.7	0.2	4.9	0.7	1.5	
		MGW	6.8	–	5033	17.2	6.4	26.5	0.2	35.4	10.9	4.6	
		SW	100	–	49,000	18.9	97.1	408.9	7.4	507.0	52.9	3.0	

FGW- fresh groundwater, MGW- mixed groundwater, SGW e saline groundwater, SW- seawater.

Seawater Intrusion Indicator Charts



Seawater Intrusion Index
Geoprocessing – Statistics - QA

- The GQI($_{SWI}$) results were compared to traditional methods that assess seawater intrusion (e.g. TDS, EC, $f$sea.
- The GQI($_{SWI}$) has been used to develop seawater intrusion vulnerability maps in GIS using a multistep process (Babiker et al. 2007) capturing the spatial variability of seawater intrusion through multiple observed concentrations (Shown next slide).
- The aim of the GQI($_{SWI}$) was to simulate seawater intrusion in coastal aquifers and is best suited to assess aggregate behavior occurring over a period of time (e.g. season, year). The model is not intended to simulate groundwater salinity originating from other sources such as paleo-hydrogeological conditions, evaporate rock dissolution, or anthropogenic pollution (Custodio, 1987).
- For performance assessment in the geostatistical component (kriging) and prior to using any interpolation model that considers spatial auto-correlation, tests were performed to confirm whether or not spatial auto-correlation will impact the results.

Geoprocessing Seawater Intrusion Index $GQI_{(swi)}$

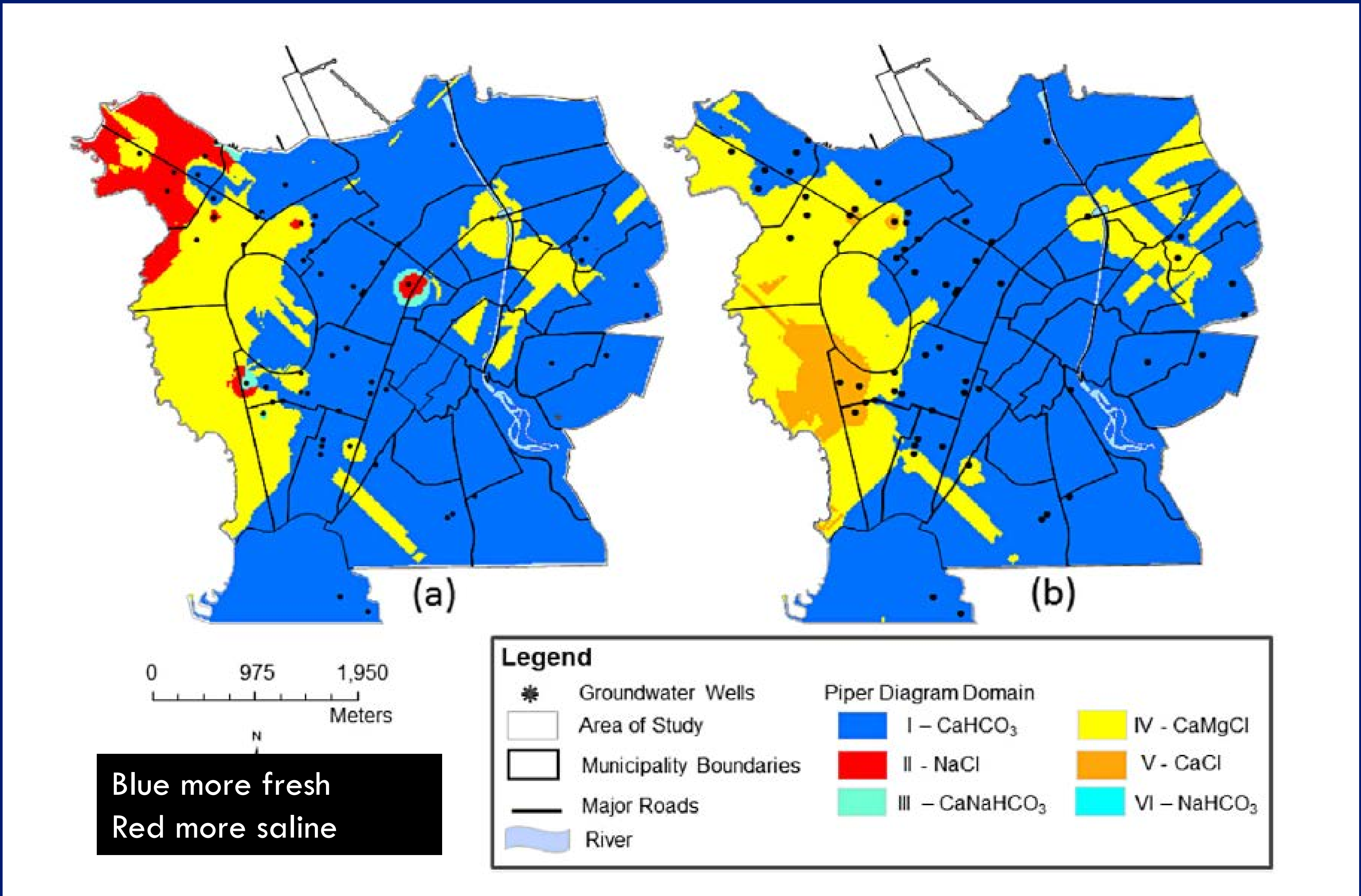
- Geoprocessing uses Vulnerability Maps to show the current position of saline intrusion and the advancing pollution plume with regard to aquifer conditions. Water quality data from wells show seawater intrusion changes laterally and vertically on the maps. The preferential routes for the seawater intrusion are also determined and included. Finally, Vulnerability Maps show areas where there is a probability of seawater intrusion in the future.

- Vulnerability maps can be produced to show areas that should be closely monitored for seawater intrusion. Mapping the seawater intrusion data for select trend wells will help to find the isochlors and wells with changing seawater intrusion problems and/or background conditions.

- Probability maps can be produced to show how conditions are expected to change in the future. This provides a way to identify very important areas of possible mixing zones and movement of seawater intrusion.

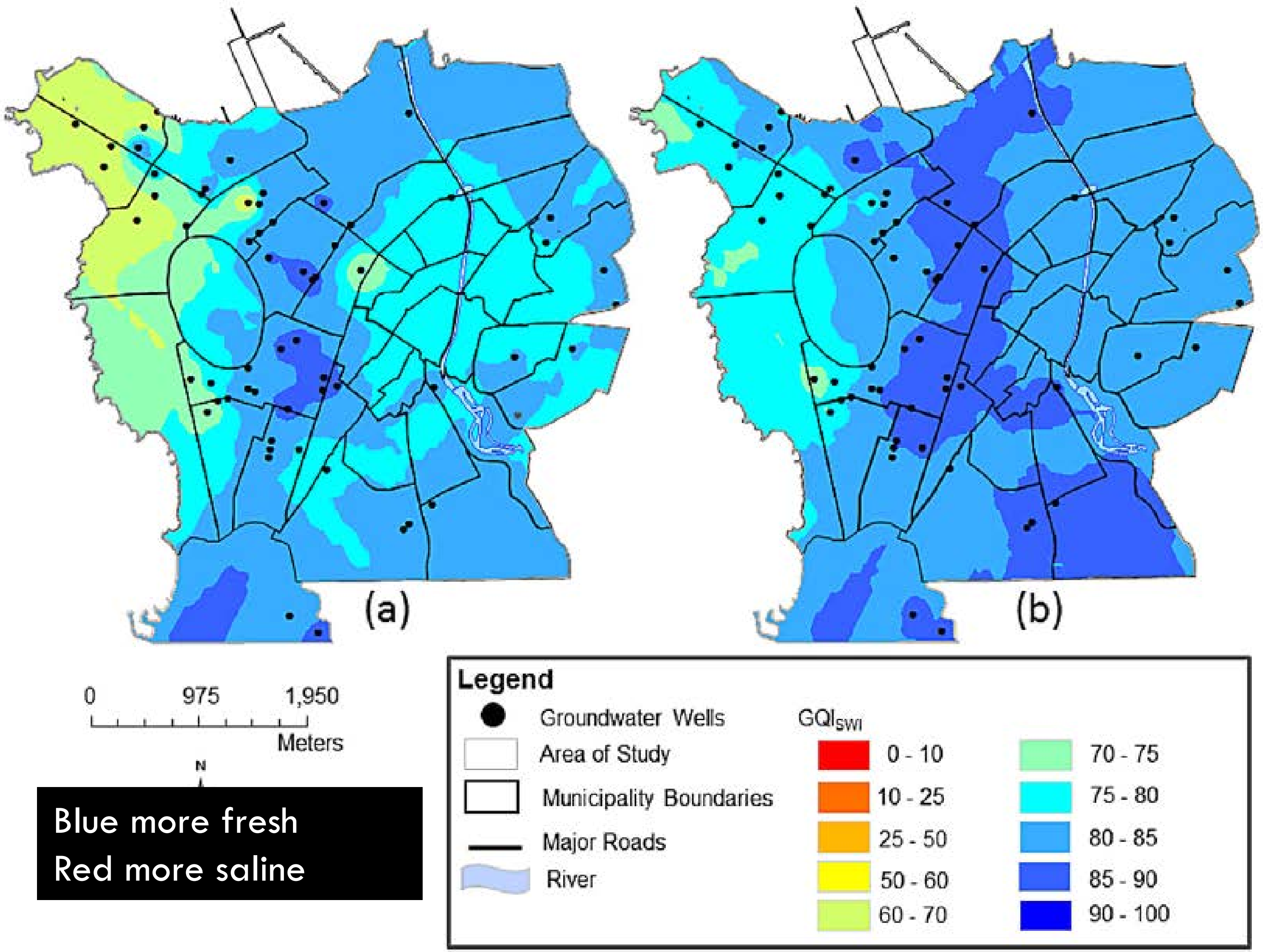
- Several map types are included in the upcoming slides to provide some examples of the different possibilities.

Wells Vulnerability Map - Piper Diagram Domains



Blue more fresh
Red more saline

Wells Vulnerability Map – GQIswi Index



Blue more fresh
Red more saline

Probability for Exceedances –Cl meq/l

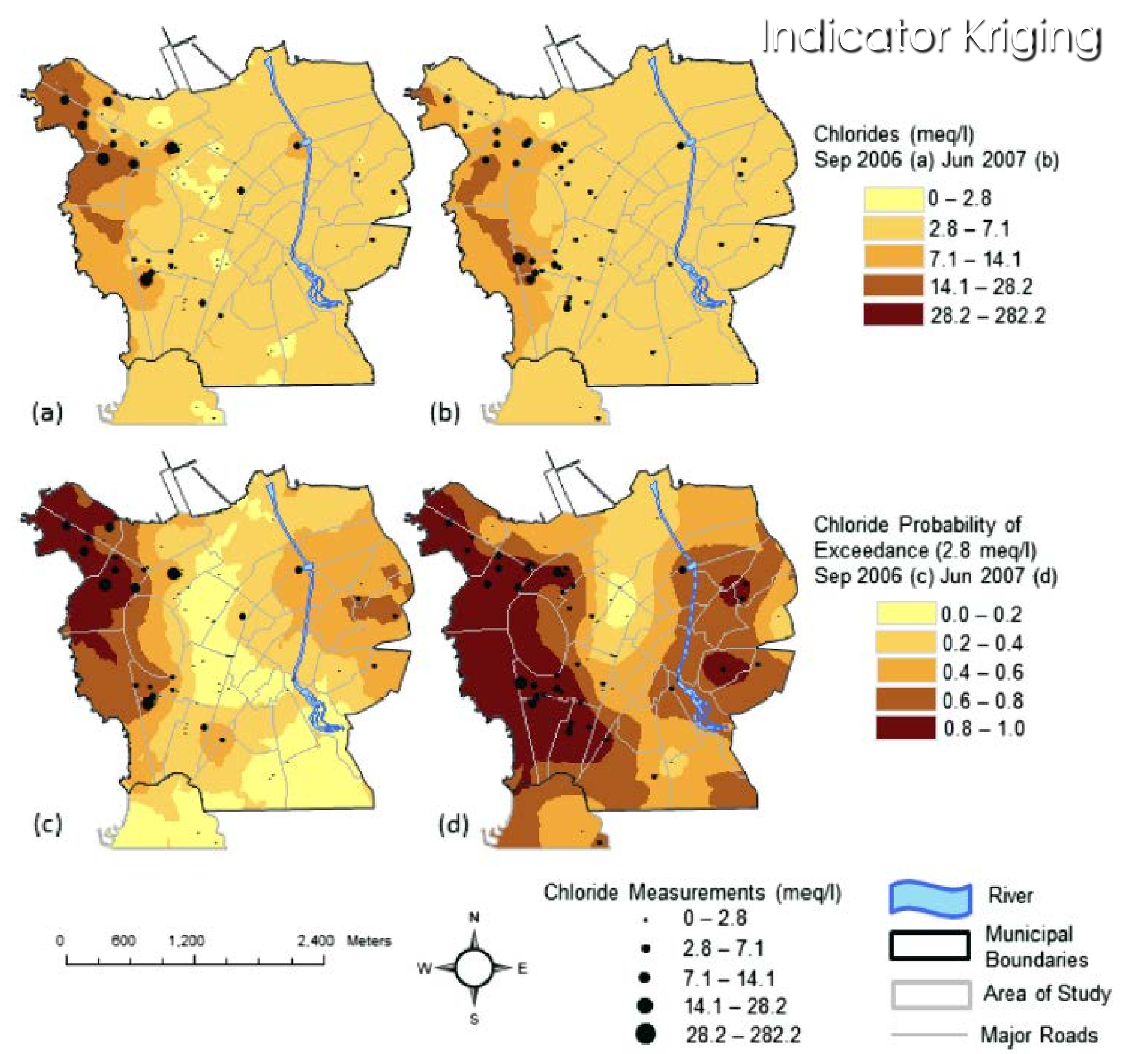


Fig. 10. Chloride concentration maps (from OK) for September 2006 (a) and June 2007 (b) and probability of exceeding threshold for salinity (from IK) for September 2006 (c) and June 2007 (d).

For More Information

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