REVIEW: “An Evaluation of a Field-Based Aquatic Benchmark for Specific Conductance in Northeast Minnesota” (November 2015). Prepared by B. L. Johnson and M. K. Johnson for WaterLegacy.

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DATE: February 4, 2016

Introduction

The evaluation by Johnson and Johnson (2015) examined the ionic mixtures of mining effluents and their impact on northeast Minnesota waters. The authors made the following inference: Because organisms (benthic macroinvertebrates) are extirpated in Appalachian streams by mineral additions that increase specific conductivity (SC)[1] to 300 microsiemens per centimeter (µS/cm) where natural background is 146 µS/cm (U.S. EPA, 2011), then organisms in waters of northeast Minnesota waters are likely to be affected by the same levels given a similar mineral composition.

“Northeast Minnesota waters” defined by Johnson and Johnson (2015) refers to a portion of the Northern Lakes and Forests Level III Ecoregion 50 (Omernik, 1987), which includes parts of the Boundary Lakes and Hills (50n), the northern portion of Toimi Drumlins (50p), and North Shore Highlands (50t). The Minnesota Pollution Control Agency (MPCA, 2016) describes the Northern Lakes and Forests on their website:

> “This heavily forested ecoregion is made up of steep, rolling hills interspersed with pockets of wetlands, bogs, lakes and ponds. Lakes are typically deep and clear, with good gamefish populations. These lakes are very sensitive to damage from atmospheric deposition of pollutants, storm water runoff from logging operations, urban and shoreland development, mining, inadequate wastewater treatment, and failing septic systems” (MPCA accessed 1/5/2016).

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[1] This review uses conductivity as a measure of ionic concentration rather than as description of an electrical property of water. As ionic concentration increases, conductivity increases. Both specific conductivity and specific conductance are often used synonymously in the open literature indicating normalization or measurement at 25°C. Conductivity is a property of water expressed in units of micro-Siemens per centimeter (µS/cm). Conductance of a sample or electrical component is measured as Siemens (S). All measurements in this review refer to specific conductivity, µS/cm at 25°C and background is estimated as the 25th centile of SC measurements.

The Johnson and Johnson (2015) evaluation describes the ionic mixture of effluents in northeast Minnesota. In Appalachia (U. S. EPA, 2011) and northeast Minnesota, the ionic mixture is dominated by bicarbonate and sulfate anions and calcium and magnesium cations (Thingvold et al., 1979). This finding is consistent with dominant ions for Ecoregion 50 (including Minnesota, Wisconsin, and Michigan) reported by Griffith (2014), whose study Johnson and Johnson (2015) did not cite. The data set used in the Johnson and Johnson study had a reported mean (note: not the 25th centile) background SC of 68 µS/cm in the defined regions of Ecoregion 50 (parts of 50n, 50p, and 50t). This is less than the 25th centile SC of the data set used in the development of the central Appalachian benchmark (146 µS/cm). The Johnson and Johnson (2015) report provides evidence that where the SC is high, there are disturbed environments. In particular, the mean and maximum SC in their study area increase below mineral effluent discharges associated with mines in the northeast region of Minnesota.

The study also provides evidence that benthic invertebrates are adversely affected where SC is greater than background. Where SC is greater than background, benthic invertebrate diversity and abundance decreases and the proportion of dominant genera increases. Attachment A, Table 1 of Johnson and Johnson (2015) identified the genera occurring in both central Appalachia and northeast Minnesota.

Overall, the weight of evidence supports the inference that effluents that increase waterbody SC to more than 300 µS/cm have adverse effects in northeast Minnesota waters. Using effect levels developed in central Appalachia, more than 5% of these shared genera are likely to be extirpated in waters with SC >300 µS/cm.

Confirmation using independent data sets

Benthic invertebrate and water quality data sets collected by the MPCA had been made available to the U.S. Environment Protection Agency (EPA) for research on stressor-response relationships. These data are used here to assess the validity of the Johnson and Johnson's findings. In Ecoregion 50, the MPCA data set consists of 40,585 water chemistry samples collected from less than 2000 sites between 1996−2013, with most of the water chemistry samples collected from repeated sampling in the same location in the same year between June and September. Annual site averages (geometric means) for SC and several other measured water quality parameters were calculated. The mean, median, minimum, maximum, and several quantiles for the population of sites in the data set are shown in Table 1.

Table 1. Summary statistics of annual geometric mean water chemistry parameters for Ecoregion 50 (MPCA, 1996−2013) prepared for this review. Mean, minimum, 5th–95th quantiles, and maximum are shown.

Parameter	*N*	Mean	Min	5th	10th	25th	50th	75th	90th	95th	Max
SC (µS/cm)	1,409	210	23	64	83	135	222	338	461	567	1,458
Alk (mg/L, unfiltered)	293	78.4	7.9	17.1	24.8	47.0	90.8	142	220	249	363
Chl a (µg/L)	200	2.3	0.5	0.8	1.0	1.5	2.3	3.7	5.2	6.6	14.6
DO (mg/L)	1,362	8.8	0.1	4.7	5.8	7.5	9.0	10.2	11.3	11.9	17.2
NH_3 (mg/L)	616	0.06	0.00	0.02	0.03	0.04	0.05	0.07	0.14	0.22	1.24
NO_x (mg/L)	850	0.09	0.00	0.02	0.03	0.05	0.07	0.15	0.34	0.63	20.8
OP (filtered, mg/L)	149	0.015	0.004	0.005	0.006	0.010	0.012	0.025	0.045	0.078	0.32
OP (unfiltered, mg/L)	339	0.013	0.001	0.005	0.005	0.007	0.011	0.020	0.037	0.058	0.61
TDS (mg/L)	165	170	49	62	70	117	200	250	307	372	780
TKN (mg/L)	632	0.77	0.20	0.43	0.50	0.59	0.74	0.96	1.29	1.54	3.91
TN (mg/L)	799	0.84	0.12	0.44	0.50	0.62	0.79	1.05	1.49	1.95	21.5
TP (mg/L)	1,151	0.043	0.003	0.015	0.019	0.026	0.042	0.066	0.102	0.154	0.91
Transp (cm)	1,768	71.5	4.9	33.6	45	60	79	99	100	100	122
TSS (mg/L)	1,217	6.4	1.0	1.7	2.0	3.0	5.1	10.4	28.3	50.9	1,076
Turbidity (NTU)	223	8.1	0.6	1.7	1.9	2.9	5.9	17.1	52.2	117.0	453

Alk = alkalinity; Chl a = chlorophyll a; DO = dissolved oxygen; NH_3 = ammonia; NO_X = oxides of nitrogen; OP = orthophosphate; TDS = total dissolved solids; TKN = total Kjeldahl nitrogen; TN = total nitrogen; TP = total phosphorous; Transp = transparency; TSS = total suspended solids; NTU = nephelometric turbidity units.

Background conductivity

The 25th centile of all samples from the MPCA data set (years: 1996−2013) was used to estimate the background SC for seven Level III ecoregions in Minnesota (see Figure 1). The estimated background SC for the entire Level III Ecoregion 50 in northeastern Minnesota is 135 µS/cm (90% confidence interval [CI] 130−140 µS/cm, *N* = 1,409). A number of the MPCA sampling sites had paired biological and chemical measurements. The 25th centile estimated background SC for sites with paired MPCA biological and chemical measurements was 108 µS/cm (90% CI 97−116 µS/cm, *N* = 735). Estimates were not made for the Level IV Ecoregions. Using either data set, Ecoregion 50 has the lowest background SC among the ecoregions in Minnesota (see Figure 1).

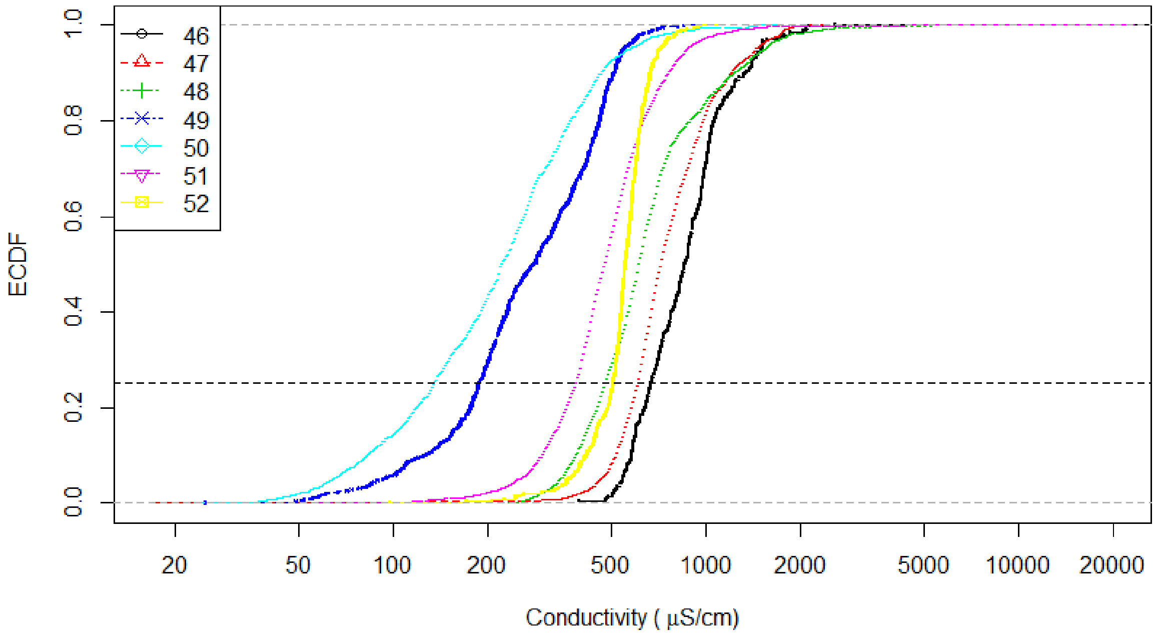

Figure 1. **Empirical cumulative distribution function (ECDF) of annual geometric mean conductivity values in ecoregions of Minnesota.** The dark horizontal dashed line is the 25th centile of ECDF. Ecoregion 50 is the Minnesota ecoregion with the lowest background SC and is plotted at the far left in turquoise (data: MPCA, 1996−2013).

Another water chemistry analysis was published in 2014 by Griffith for the entire Ecoregion 50 extending from northeastern Minnesota through Wisconsin and into northern Michigan. These published results were generated from data sets compiled from several EPA surveys that used probability-based sampling designs (Griffith, 2014). The 25th centile SC for that data set at the Level III Ecoregion 50 was 111 µS/cm (*N* = 151), which is less than in the Appalachian study data set.

In comparison, Table 2 contains values from the Minnesota Environmental Quality Board MEQB (1979), which were collected between 1975 and 1977. This earlier sampling effort is confined to an area of interest consisting of 14 watersheds that are included in the Johnson and Johnson evaluation (2015). The median stream SC is reported as 55 µS/cm. Johnson and Johnson (2015) report a mean of 68 µS/cm using data from a comparable time period. Both values are less than the 25th centile background in Appalachia streams (U.S. EPA, 2011).

Based on these independent data sets, it appears that, currently and 40 years ago, the background SC in the study area has been less than the background estimated from the data set used to derive the conductivity benchmark for the combined Appalachian Ecoregions 69 and 70 (U. S. EPA, 2011). This confirms the Johnson and Johnson claim.

Table 2. Data from Minnesota Environmental Quality Board collected between 1975 and 1977 from streams in "Group C stations" and reproduced here for the reader's convenience

Parameters	Median stream value
Specific conductivity (µS/cm) (25°C)	55
Al (µg/L)	90
As (µg/L)	0.8
Ca (mg/L)	6.0
Cd (µg/L)	0.03
Cl (mg/L)	1.6
Co (µg/L)	0.4
Cu (µg/L)	1.3
Fe (µg/L)	560
F (mg/L)	310
Hg (µg/L)	0.08
K (mg/L)	0.6
Mg (mg/L)	3
Mn (µg/L)	35
Na (mg/L)	1.6
Ni (µg/L)	1.0
Pb (µg/L)	0.5
Zn (µg/L)	2.0
Alkalinity (mg/L))($CaCO_3$)	19
TOC (mg/L)	15
P-total (µg/L)	20
Total Nitrogen (mg/L)	0.79
SO_4 (mg/L)	6.6
pH	6.9
Color (Pt-Co scale)	90.2
Silica (mg/L)	6.3

TOC = total organic carbon; P-total = total phosphorous; Pt-Co = platinum-cobalt.

Biological effect

Extirpation is the loss of a taxon from its normal habitat, such as a portion of a stream or geographic area. For this review, the concentration resulting in extirpation is defined as the SC level above which less than 5% of observations of a genus were made in an ecoregion, an extirpation concentrations (XC_{95}) (U. S. EPA, 2011).

Johnson and Johnson (2015, Attachment A, Table 1 of their report) identified the benthic macroinvertebrate genera occurring in both Appalachia and northeast Minnesota streams. They used XC_{95} values for Appalachian genera to evaluate extirpation of the same genera in northeast Minnesota streams. Using effect levels developed in central Appalachia, more than 5% of these shared genera are likely to be extirpated in waters with SC >300 µS/cm. Because Johnson and Johnson did not use Minnesota data to calculate effect levels for individual genera in northeastern Minnesota streams, there is uncertainty whether the species comprising a genus in Minnesota is similar enough to those in West Virginia for comparison. This point is important because the extirpation concentration (XC_{95}) values represent the effect level for the most tolerant species in that genus.

We were able to overcome this limitation for this review because we had a paired biological and SC data from Ecoregion 50 in Minnesota. Using the MPCA data set, we directly calculated XC_{95} levels for benthic invertebrates in northeastern Minnesota streams. Then, we used these Ecoregion 50-Minnesota XC_{95} values to predict the SC at which 5% of benthic invertebrate genera are likely to be extirpated.

Estimation of specific conductivity (SC) likely to cause extirpation

Paired biological and chemical data were analyzed using the MPCA data set from 1996−2013 (see Figure 2) and using the methods described in EPA (2011). XC_{95} values were calculated for 164 genera (see Table 3) that occurred at $\geq$25 sites in the MPCA paired data set (see Figure 2) using the methods in EPA (2011). Although the number of sites was modest (number of samples was 734, number of sites was 596) and the range of SC values is limited, the tolerance range was defined for more than 12% of genera that were analyzed, which allowed confident estimation of the SC that would result in the loss of 5% of genera.

Estimation of the specific conductivity (SC) likely to extirpate 5% of genera

In this review, extirpation of 5% of genera was used as the effect threshold. The SC level predicted to cause 5% extirpation is referred to as the hazardous concentration (HC_{05}) (U.S. EPA, 2011). Using the available data set, the interpolated 5th centile of the ranked XC_{95} values (HC_{05}) for Ecoregion 50 in Minnesota is 320 µS/cm. Note that even if a genus is not extirpated at the HC_{05}, the abundance or ecoregion occurrences may still be reduced. The

Minnesota HC_{05} for Ecoregion 50 (320 µS/cm) is similar to the HC_{05} of the Appalachian study (295 µS/cm).

Most samples in the MPCA data set were collected during August and September, and many salt-intolerant genera may not have been collected because they are more likely to be collected earlier in the year. Therefore, this HC_{05} may be higher than would be obtained with a data set that included more mayfly genera which are collected in the spring and tend to be among the more intolerant genera. Also, the estimated HC_{05} is for this review only and it does not represent a benchmark for Ecoregion 50. Additional analyses are recommended to evaluate the seasonal effects in the data set that was used for the estimate.

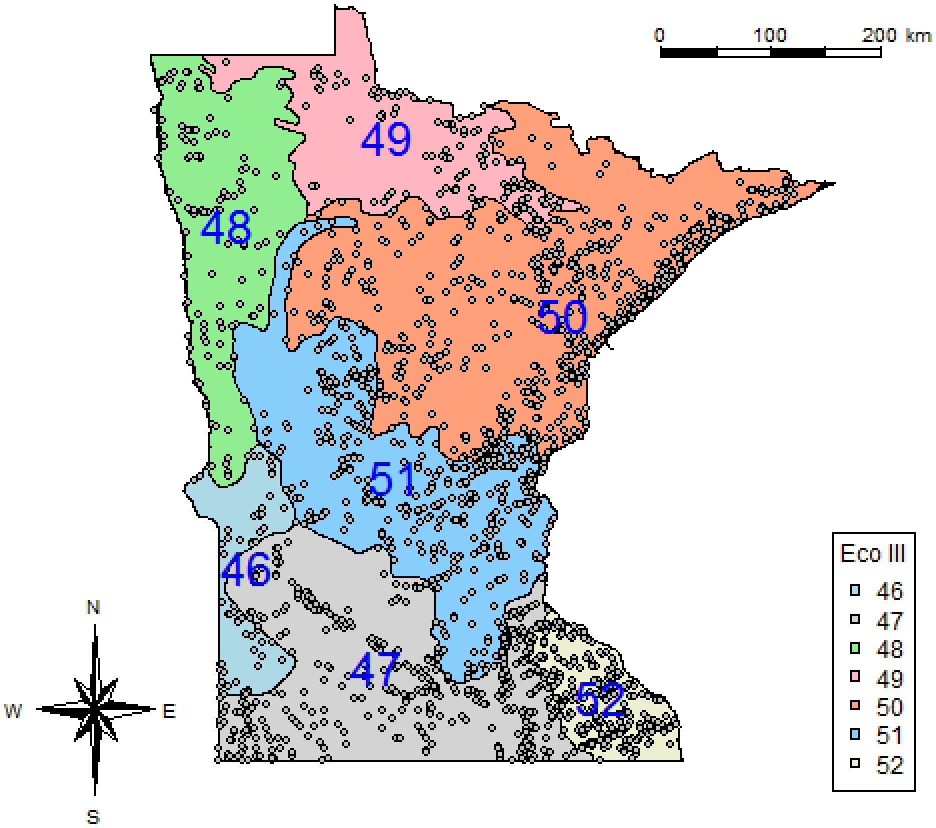

Figure 2. Ecoregion 50 is contained in the orange area in the northeast portion of Minnesota. Circles represent paired biological and water quality sampling sites. There are fewer samples in the area bordering Canada, often referred to as the boundary waters, which are less accessible for sampling.

Table 3. XC$_{95}$ values for 164 genera with $\geq$25 occurrences in Ecoregion 50 of Minnesota prepared for this review

Genus	XC$_{95}$ µS/cm	Samples	Genus	XC$_{95}$ µS/cm	Samples	Genus	XC$_{95}$ µS/cm	Samples
Dolophilodes	191	82	*Protoptila*	717	106	*Rheotanytarsus*	912	477
Epeorus	201	94	*Psychomyia*	717	71	*Tvetenia*	912	347
Rhyacophila	254	35	*Pycnopsyche*	717	51	*Nilothauma*	1,008	71
Ophiogomphus	272	73	*Chimarra*	719	277	*Dicranota*	1,029	70
Serratella	283	40	*Ephemera*	719	44	*Chrysops*	1,110	38
Boyeria	298	117	*Ephemerella*	719	144	*Clinotanypus*	1,110	31
Agnetina	302	25	*Nyctiophylax*	719	30	*Gammarus*	1,110	40
Trissopelopia	327	25	*Paratendipes*	719	67	*Sigara*	1,110	52
Xenochironomus	335	36	*Pteronarcys*	719	82	*Ceraclea*	1,134	140
Larsia	338	25	*Stenonema*	719	184	*Neophylax*	1,134	26
Paraponyx	338	33	*Dixa*	736	28	*Nigronia*	1,134	101
Eurylophella	357	151	*Neoplea*	736	71	*Potthastia*	1,134	30
Stictochironomus	361	46	*Stenochironomus*	736	205	*Stempellina*	1,134	112
Helisoma	374	95	*Xylotopus*	736	64	*Chironomus*	1,138	86
Lopescladius	390	60	*Hexagenia*	829	32	*Zavrelimyia*	1,138	34
Leptophlebia	416	43	*Stenacron*	859	125	*Micrasema*	1,182	162
Leucrocuta	435	124	*Acroneuria*	867	225	*Antocha*	1,185	123
Labiobaetis	456	55	*Atherix*	867	211	*Cryptochironomus*	1,185	83
Plauditus	464	38	*Endochironomus*	867	53	*Dicrotendipes*	1,185	197
Triaenodes	502	58	*Isonychia*	867	98	*Glyptotendipes*	1,185	47
Nilotanypus	510	50	*Neureclipsis*	867	127	*Taeniopteryx*	1,185	33
Nectopsyche	529	56	*Labrundinia*	872	198	*Conchapelopia*	1,353	51
Liodessus	559	73	*Oecetis*	872	329	*Gyraulus*	1,353	107
Procloeon	568	131	*Paragnetina*	872	161	*Hydropsyche*	1,353	294
Callibaetis	620	26	*Sublettea*	872	28	*Limnephilus*	1,353	25
Cryptotendipes	620	35	*Tricorythodes*	872	141	*Nanocladius*	1,353	140
Valvata	620	26	*Enallagma*	879	53	*Tanytarsus*	1,353	511
Ancyronyx	626	45	*Parakiefferiella*	879	134	*Thienemannimyia*	1,353	524
Hexatoma	626	37	*Brachycentrus*	882	113	*Hydraena*	1,370	86
Atrichopogon	630	29	*Macronychus*	882	159	*Ablabesmyia*	1,412	297
Acentrella	650	164	*Rheocricotopus*	882	163	*Helicopsyche*	1,412	213
Cardiocladius	650	30	*Probezzia*	912	40	*Maccaffertium*	1,412	244
Glossosoma	650	191	*Psectrocladius*	912	105	*Microtendipes*	1,412	412

Table 3. XC_{95} values for 164 genera with ≥25 occurrences in Ecoregion 50 of Minnesota prepared for this review (continued)

Genus	XC_{95} µS/cm	Samples	Genus	XC_{95} µS/cm	Samples	Genus	XC_{95} µS/cm	Samples
Pseudochironomus	1,412	27	*Anacaena*	1,594	39	*Dixella*	1,998	102
Stenelmis	1,412	302	*Anopheles*	1,594	79	*Eukiefferiella*	1,998	198
Tribelos	1,412	66	*Baetis*	1,594	402	*Ferrissia*	1,998	348
Thienemanniella	1,417	259	*Ceratopsyche*	1,594	436	*Haliplus*	1,998	109
Micropsectra	1,426	275	*Cladotanytarsus*	1,594	97	*Hydatophylax*	1,998	88
Polypedilum	1,442	628	*Dubiraphia*	1,594	371	*Iswaeon*	1,998	87
Cricotopus	1,447	508	*Gyrinus*	1,594	60	*Limnophyes*	1,998	69
Hemerodromia	1,447	308	*Hyalella*	1,594	436	*Mystacides*	1,998	95
Parachironomus	1,447	34	*Lype*	1,594	62	*Orconectes*	1,998	54
Pentaneura	1,447	56	*Simulium*	1,594	463	*Orthocladius*	1,998	219
Corynoneura	1,451	274	*Somatochlora*	1,594	35	*Paraleptophlebia*	1,998	217
Cheumatopsyche	1,458	422	*Tipula*	1,594	120	*Paramerina*	1,998	120
Hydroptila	1,458	223	*Physa*	1,818	387	*Parametriocnemus*	1,998	286
Isoperla	1,458	42	*Caenis*	1,825	369	*Phaenopsectra*	1,998	187
Optioservus	1,458	401	*Acerpenna*	1,998	251	*Polycentropus*	1,998	138
Oxyethira	1,458	233	*Aeshna*	1,998	79	*Procladius*	1,998	205
Paratanytarsus	1,458	238	*Baetisca*	1,998	41	*Pseudocloeon*	1,998	82
Amnicola	1,527	80	*Belostoma*	1,998	75	*Ptilostomis*	1,998	97
Bezzia	1,527	94	*Brillia*	1,998	118	*Sialis*	1,998	88
Cordulegaster	1,527	29	*Caecidotea*	1,998	39	*Stempellinella*	1,998	330
Fossaria	1,527	49	*Calopteryx*	1,998	259	*Synorthocladius*	1,998	47
Lepidostoma	1,527	267	*Centroptilum*	1,998	67			

Conclusion

The results of the analyses performed for this review support the conclusions of Johnson and Johnson (2015) concerning the effects of SC on benthic invertebrates.

1. Independent data sets from different decades confirm Johnson and Johnson's conclusion that the background SC in Ecoregion 50 in Minnesota is less than the background of the data set used to develop the SC benchmark for Ecoregions 69 and 70 in Central Appalachia. Hence, a benchmark value for SC in Ecoregion 50 is not expected to be greater than the benchmark for central Appalachia, i.e. 300 µS/cm.

2. Likewise, the inference that 5% extirpation of benthic invertebrates would occur at similar conductivity levels in central Appalachia and Ecoregion 50 in Minnesota was supported by analysis of an independent data set of paired benthic invertebrate and SC data from Ecoregion 50 in Minnesota. We estimated that more than 5% of genera would be extirpated in streams greater than 320 µS/cm. However, additional analyses are needed to evaluate the effect of seasonal collection.
3. Johnson and Johnson evaluated biological effects where SC was greater than background at several mine sites and streams draining in or near the mines. SC associated with discharges and mine pits exceeded 300 µS/cm. For some sites, dilution may reduce the SC below 300 µS/cm in the waterbody, but the data are not shown and may not be available for all sites. In other cases, SC is very high (>1,000 µS/cm) and biological effects have been reported by MPCA. The severity of the effects are consistent with effects expected for increased level of SC.
4. Metal contamination, habitat alteration, temperature, and nutrient enrichment may contribute to biological effects at some of the mine sites. These stressors may exacerbate the effect, but the extirpation due to SC would still occur if these stressors were removed based on removal of other stressors and persistent effects observed in Appalachia when only conductivity was high and other stressors were low or absent (U.S. EPA, 2011; Timpano et al., 2015; Cook et al., 2015).

Johnson and Johnson (2015) make several recommendations based on their findings. These are policy decisions and are not part of this scientific review.

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