Equilibrium Environmental Inc.

SYNTHESIS OF SAR/HYDRAULIC CONDUCTIVITY DATA

FROM MULTIPLE COLUMN STUDIES

COUPLED WITH THREE-DIMENSIONAL TRANSPORT MODELING

TO SUPPORT FRAMEWORK FOR

SUBSOIL SAR GUIDELINES

DRAFT REPORT

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1 INTRODUCTION

Historically, salt impacts to soil and groundwater have occurred in the upstream oil and gas industry due to produced water infrastructure failures such as pipeline breaks and tank leakage, as well as operational practices. When large amounts of sodium chloride produced water are accidentally released to soil, there are salinity and sodicity (elevated Sodium Adsorption Ratio, or “SAR”) related impacts. The negative effects of elevated sodium on surficial soil quality are well known and include the dispersion of clay particles, clay swelling, and a resultant reduction in hydraulic permeability which may lead to water logging of the rooting zone.

Within the upstream oil and gas industry there are high numbers of well sites and facilities with subsoil salinity/sodicity impacts, which require impact evaluation, remediation, and reclamation. For salt impacted sites in the upstream oil and gas industry, the depth of salinity and sodicity impacts is generally dependant on the produced water release mechanism. Although leaking tanks and surface spills of small volumes mainly impact rooting zone soils, larger spills, such as pipeline breaks and flare pit releases, typically have significant impacts below the rooting zone.

Currently SAR guidelines exist only for impacts in the root zone. There is an urgent need for the development of risk-based subsurface (below the root zone) SAR guidelines for the remediation of salt impacted sites. Uncertainty with application of root zone SAR guidelines for deeper soils is a significant roadblock for site remediation and reclamation. As a result, remediation may be delayed due to such uncertainty, or remediation of subsoil using generic rooting zone SAR guidelines may result in an over or under protection. For instance, unnecessary volumes of soil may be removed, leading to an inefficient use of energy and resources. Incomplete understanding of subsurface sodicity in the use of common remediation techniques that rely on the leaching of salts through the soil column may also be associated with deleterious effects on subsoil structure.

The overall objective of the project is to increase the level of knowledge on the effects of sodicity and elevated SAR values on water transport in soils, as well as on soil structure, at contaminated sites associated with upstream oil and gas operations. The knowledge gained will assist in the generation of risk-based guidelines to assess the effects of SAR impacts on subsoils by using appropriate endpoints for subsoil structure. An improved determination of what is a considered a deleterious impact to subsoil structure would aid in the definition of risks related to sodicity impacts and appropriate soil remediation guidelines.

Pursuant to these goals, the following activities have been performed in previous stages of this project. The year shown refers to the date of the referenced report (Equilibrium Environmental 2010 or Equilibrium Environmental 2011), summarizing research from 2009-2010 and 2010-2011 project phases respectively.

- Detailed literature review on the effects of SAR on soil structure, including the effects of factors such as texture, clay mineralogy, pH, organic matter, soil saturation, and other factors on the SAR/EC threshold curves (2010)
- Preliminary collection of soil cores from a range of sites across Alberta (2010)

- Initial development of leaching column methodology including a comparison of intact vs undisturbed cores, compaction levels, etc (2010)
- Preliminary leaching column experiments to allow initial comparison of SAR/EC/K_{sat} responses to literature examples (2010)
- Preliminary evaluation of the reversibility of SAR-induced hydraulic conductivity losses (2010)
- Continued refinement of the leaching column testing methodology (2011)
- Collection of additional field cores from new locations and geographical regions in Alberta (2011)
- Performed additional leaching column experiments, with a focus on a broader range of SAR values (from 10 to 115) and soil textures (coarse sandy soils and high clay-content, low-conductivity soils) (2011)
- Performed preliminary water table modeling to help determine appropriate thresholds for acceptable hydraulic conductivity losses which are unlikely to cause a water-logged root-zone (2011)
- Continued evaluation of the reversibility of SAR effects via remediation (2011)
- Preliminary framework for guideline development proposed for the soil structure pathway (additional details below) (2011)

The previous stage of this research (Equilibrium 2011) proposed a preliminary framework for subsoil SAR guideline development, with a particular emphasis on the hydraulic conductivity / soil structure risk pathway. This was based on a combination of the leaching column data generated up to that point combined with preliminary water table modeling in order to estimate the potential for a water-logged root-zone. Both the leaching column experiments and water table modeling were subsequently expanded and refined in the 2011-2012 research.

As a follow-up to this previous work, the following activities were performed in this stage of the project (2011-2012) and are summarized herein:

- Further collection of field soils from additional geographical regions and textures, primarily in undisturbed, intact soil cores
- Additional leaching column experiments on collected soils to expand the database of soil responses to EC/SAR combinations
- Leaching column experiments were performed on organic soils to evaluate whether they behave significantly different than the typical clay-containing mineral soils
- Leaching column results from this year and the previous years were synthesized to provide an overall view of the response of typical mineral soils to EC/SAR combinations
- Comparison of synthesized leaching column experiments to literature EC/SAR thresholds to allow further extrapolation of literature thresholds in support of guideline development
- Expanded water table modeling to consider a wider range of impact sizes, depths, magnitudes, initial water table level, and vertical gradients

- Preliminary modeling of SAR/sodium transport in soils, including modeled conversions between solution and saturated paste measurements to allow comparison with experimental and theoretical values

Based on this research, an analysis of potential pathways and receptors for subsoil SAR was performed in support of guideline development. These pathways extend beyond the hydraulic conductivity / soil structure effects studied by the leaching column experiments, and also include groundwater pathways such as water sourced from a dugout. Potential mechanisms to derive guidelines for each of the pathways were evaluated, especially in the context of the proposed Subsoil Salinity Tool (SST) environment for guideline implementation. This also included an analysis of regulatory and policy issues to be further investigated and discussed as this SST implementation proceeds.

2 SAR / EC INTERACTIONS FROM LITERATURE

This section summarizes key background SAR information from literature, including important interactions between SAR, EC, and clay dispersion. Some of the information below was also presented in Equilibrium 2011, but is shown here for context along with some additional updates and additions also incorporated. Additional details such as the influence of clay type and pH are discussed in more detail in Equilibrium 2011.

2.1 GENERAL SAR INFORMATION

Elevated sodium in soil, as measured by elevated Sodium Adsorption Ration or "SAR", may be due to natural salts or introduced anthropogenically through various oil and gas operations such as those involving produced water or drilling waste. The negative effects of elevated sodium on surficial soil quality are well known and include the dispersion of clay particles, clay swelling, and a resultant reduction in hydraulic conductivity which may lead to poor infiltration or surface 'hard-pan'.

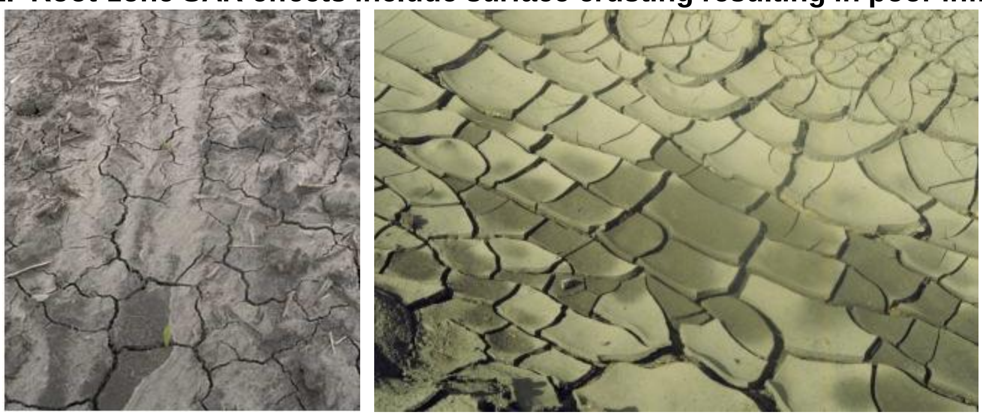
SAR is defined in the equation below (Alberta Environment, 2001 and Curtin, 1995a), with all concentrations shown on a charge basis (milliequivalents per litre). In general terms SAR thus represents the ratio of sodium to calcium plus magnesium ions, with it generally assumed that magnesium and calcium are similar in their exchange behaviour with soils (Curtin, 1994b). It is important to note that the presence of the square-root in the denominator introduces a non-linearity into the equation such that diluting a solution by 2-fold will decrease EC by approximately 2-fold but will reduce SAR by approximately 1.4-fold (square root of 2).

$$SAR = \frac{[Na]}{\sqrt{\frac{[Ca] + [Mg]}{2}}}$$

It is widely reported that water transport can be affected by relative cation concentrations as measured by SAR (Dikinya, 2007, Levy, 2005). High SAR can greatly reduce hydraulic conductivity (K_{sat}), with the magnitude of these K_{sat} losses varying widely depending on a variety of factors (Levy, 2005). K_{sat} losses are typically caused by the swelling and dispersion of clay particles, with the smectite clays common in prairie soils (Curtin, 1994b) generally susceptible to such changes along with other such "2:1" clay minerals (Shainberg, 2001).

Root-zone SAR may result in hard-pan or poor infiltration of rainwater, especially with shear from rain-drops or tillage (Figure 2.1). Root-zone SAR has been the primary focus of much of the available literature, especially in the context of the application of sodic irrigation waters such as in Curtin (1995a and 1994c) and Springer (1999). The sodic waters applied by irrigation may due to sodium chloride-based impacts or may also be due to natural sulfate salts (Springer, 1999). The periodic exposure of root-zone SAR-impacted soils to low electrical conductivity (EC) rainwater has also been shown to exacerbate these problems in some cases (Minhas, 1986), with the interactions between SAR, EC, and K_{sat} discussed in more detail in Section 2.2.

Figure 2.1. Root-zone SAR effects include surface crusting resulting in poor infiltration



Lesser quantities of research are available regarding SAR in subsoil (defined here as below the root-zone), though subsoil SAR may potentially result in water-logging of soils or creation of a perched water table. If these effects extend sufficiently far upward, the water-logging of root-zone soils could potentially impair plant growth.

2.2 SAR/EC/K_{SAT} RELATIONSHIPS FROM LITERATURE

Though elevated SAR is known to have the potential to cause deleterious soil dispersion, it has also been known for more than 50 years that elevated electrolyte concentration (EC) can help protect from these SAR effects (Quirk, 1955). The concept of EC 'thresholds' for SAR effects was introduced in this Quirk 1995 paper, with additional data and refinements related to this concept generated by numerous other researchers in the subsequent decades (Quirk, 2001). For example, it was noted that this protective effect may diminish as salt (electrolytes) are leached from soils by low-EC rainwater (Minhas, 1986). This effect may be more immediately relevant to root-zone soils than subsoils due to the closer proximity of root-zone soils to the source of low-EC rainwater. Regardless, the study of EC/SAR relationships and how they affect K_{sat} has been a common theme for SAR research over many decades.

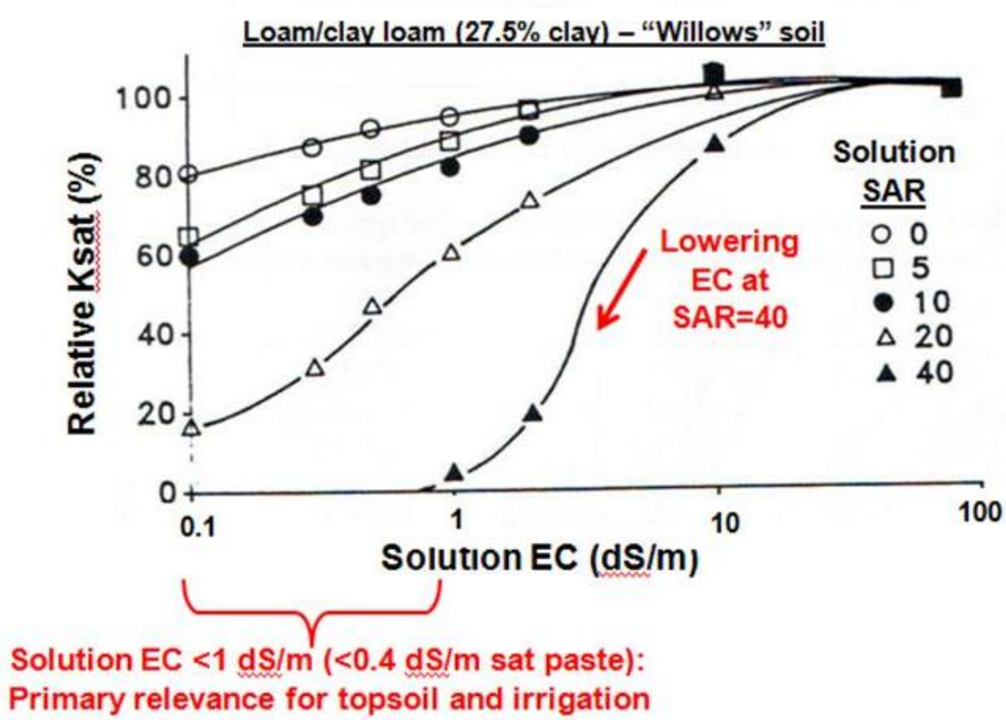
Useful research was performed by Curtin *et. al* examining SAR/EC/K_{sat} relationships through the Agriculture and Agri-Food Canada research branch in Swift Current, Saskatchewan (Curtin et al 1994a, 1994b, 1994c, 1995a, 1995b). The focus of this research was primarily topsoil, with losses in hydraulic conductivity in topsoil due to SAR potentially further exacerbated in the field by shearing due to tillage and low EC raindrops. This research also has relevance to subsoil, though these exacerbating factors such as tillage and shear by raindrops would not be present in subsoil.

This research was also targeted toward the development of irrigation thresholds, and thus evaluated a large number of solutions with EC less than 1 dS/m (Cutin, 1994c). This is likely equivalent to less than 0.4 dS/m on a saturated paste basis, and thus some of these low-EC results may be less relevant for subsoil SAR.

The experimental methodology involved repacking topsoil to a fixed bulk density, followed by pre-wetting the soil columns with tap water with EC of approximately 0.6 dS/m and SAR of approximately 1. Solutions of fixed SAR values (up to a maximum of 40) were then leached through the columns while reducing the total electrolyte concentration from approximately 80 dS/m to 0.1 dS/m. Electrolyte concentrations were expressed in meq/L in Curtin (1994c), but are shown in the figures below after converting to electrical conductivity using a typical conversion of 10:1 between meq/L and dS/m. After each change in solution EC, the columns were leached until hydraulic conductivity equilibriated, and results expressed as a percentage relative to the initial baseline.

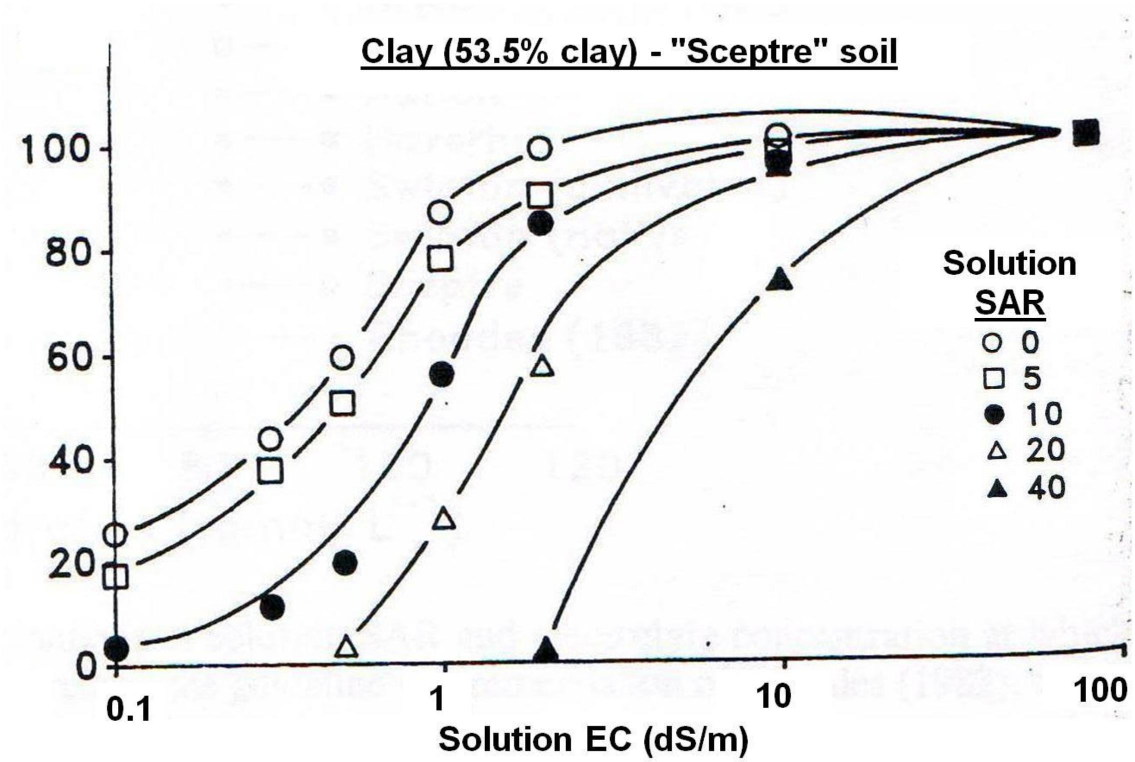
Results were found to be highly dependent on soil texture, with Figure 2.2 showing an example of EC/SAR interactions for a loam / clay loam soil with 27.5% clay (Curtin, 1994c). At the highest SAR value of 40, K_{sat} was reduced by more than 10-fold below the baseline as EC was reduced from 80 dS/m to approximately 1 dS/m. Lesser effects were seen at lower SAR values, with a significant portion of the effects occurring at solution EC below 1 dS/m. As noted previously, this range of EC below 1 dS/m has primary relevance for topsoil and irrigation, and has lesser relevance for subsoils where background salinity is often above these levels.

Figure 2.2. SAR/EC effects from literature on clay loam soil (28% clay) (Curtin, 1994c)



The behavior of soil with a higher clay content (53.5% clay) is shown in Figure 2.3 (adapted from Curtin, 1994c). A steeper reduction in hydraulic conductivity as EC decreases is noted compared to Figure 2.1, suggesting that soils with higher clay content may be more sensitive to SAR-induced K_{sat} losses. It is also noteworthy that an approximate 4-fold decrease in K_{sat} was observed at SAR=0 at extremely low EC (0.1 dS/m), though the corresponding K_{sat} reduction was less than 20% at an EC of 1.

Figure 2.3. SAR/EC effects from literature on Clay soil (54% clay) (Curtin 1994c)



In contrast, the behavior of a sandier soil with lower clay content (13% clay, “Hatton” soil) is shown in Figure 2.4 (also adapted from Curtin, 1994c). This coarse soil generally exhibited less response to SAR than the soils with higher clay content examined above. For example, a solution SAR of 40 resulted in less than a 2-fold K_{sat} reduction for solution EC above 1 dS/m. A loam soil with 17% clay is shown in Figure 2.5 (cultivated “Swinton” soil), showing a fairly similar response to the above-noted sandy loam.

Figure 2.4. SAR/EC effects from literature on sandy loam (13% clay) (Curtin 1994c)

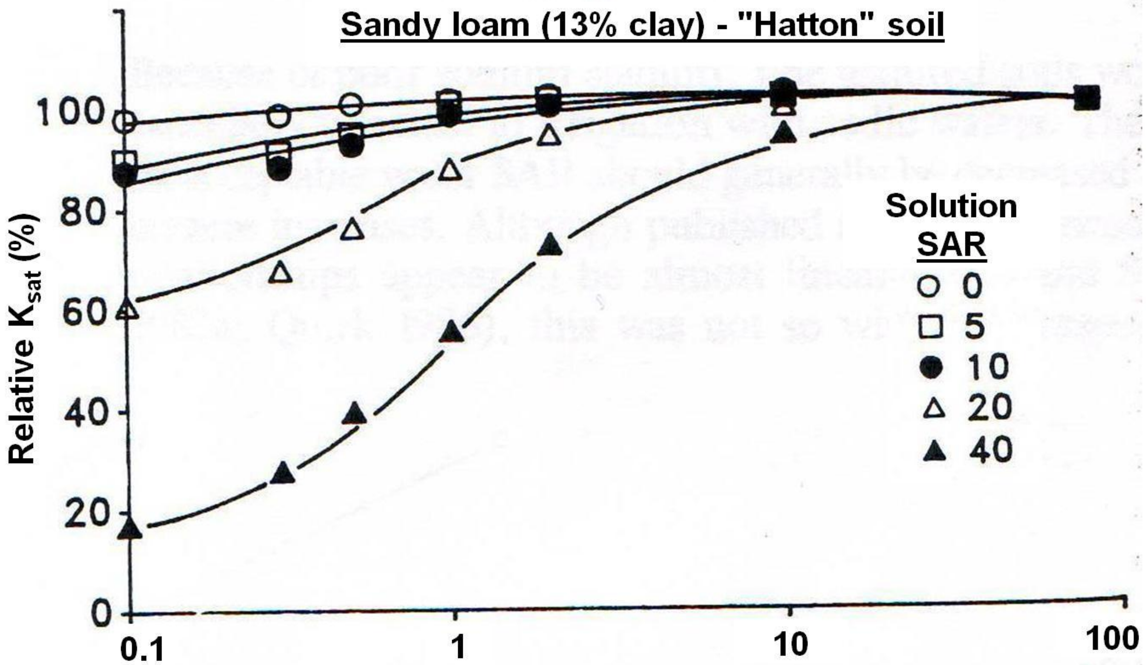
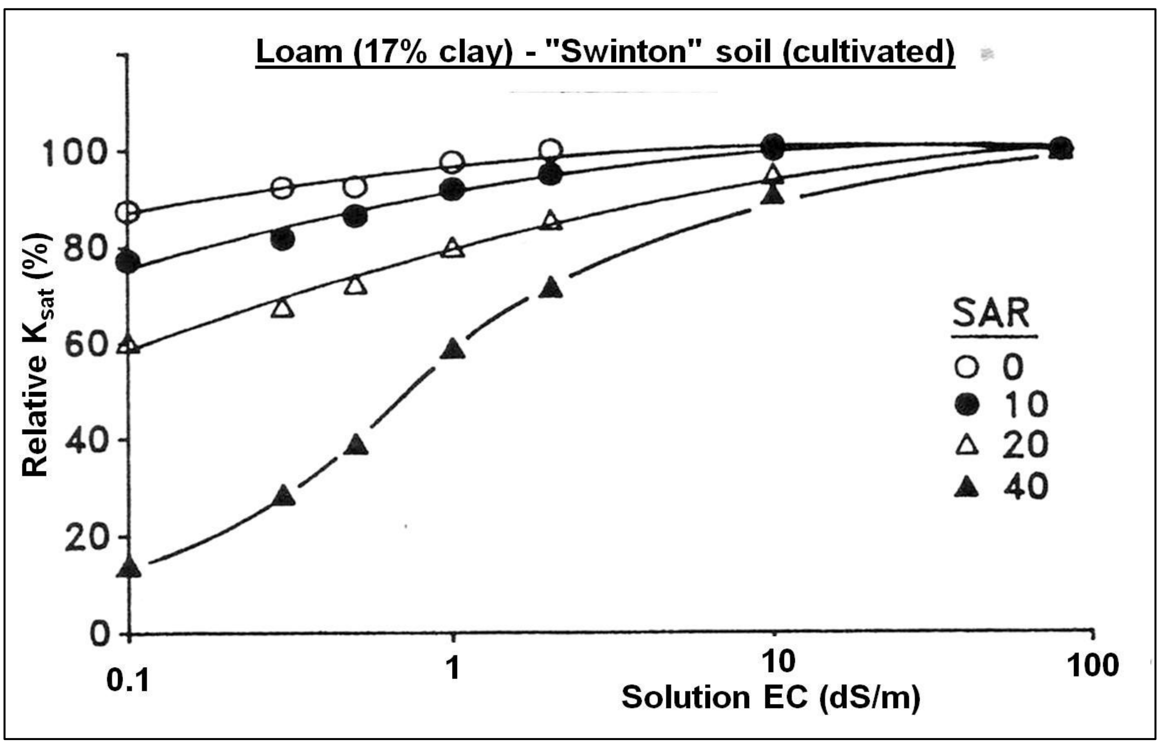
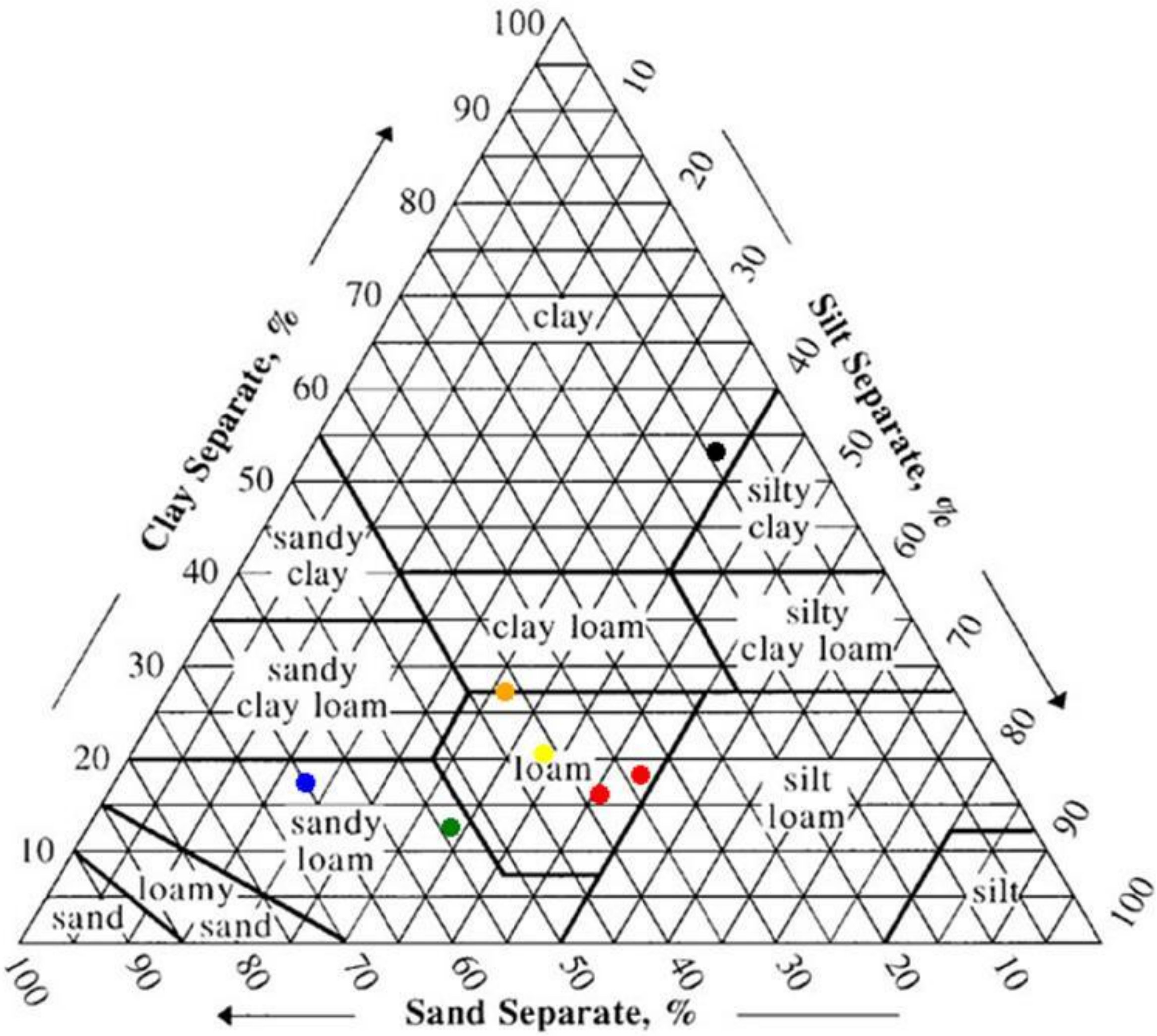


Figure 2.5. SAR/EC Effects from literature on loam soil (17% Clay) (Curtin, 1994c)



These examples provide empirical evidence that clay content (and hence soil texture) play a significant role in determining the sensitivity of any individual soil to SAR / EC combinations. Figure 2.6 summarizes the various textures tested in Curtin 1994c, including two sandy loams (13-18% clay), three loams (17-21% clay), one clay loam (28% clay), and one clay (54% clay). This wide range of coarseness and clay content is considered to be representative of large portions of prairie soils throughout Alberta and Saskatchewan.

Figure 2.6. Summary of Soil Types Tested in Curtin, 1994c



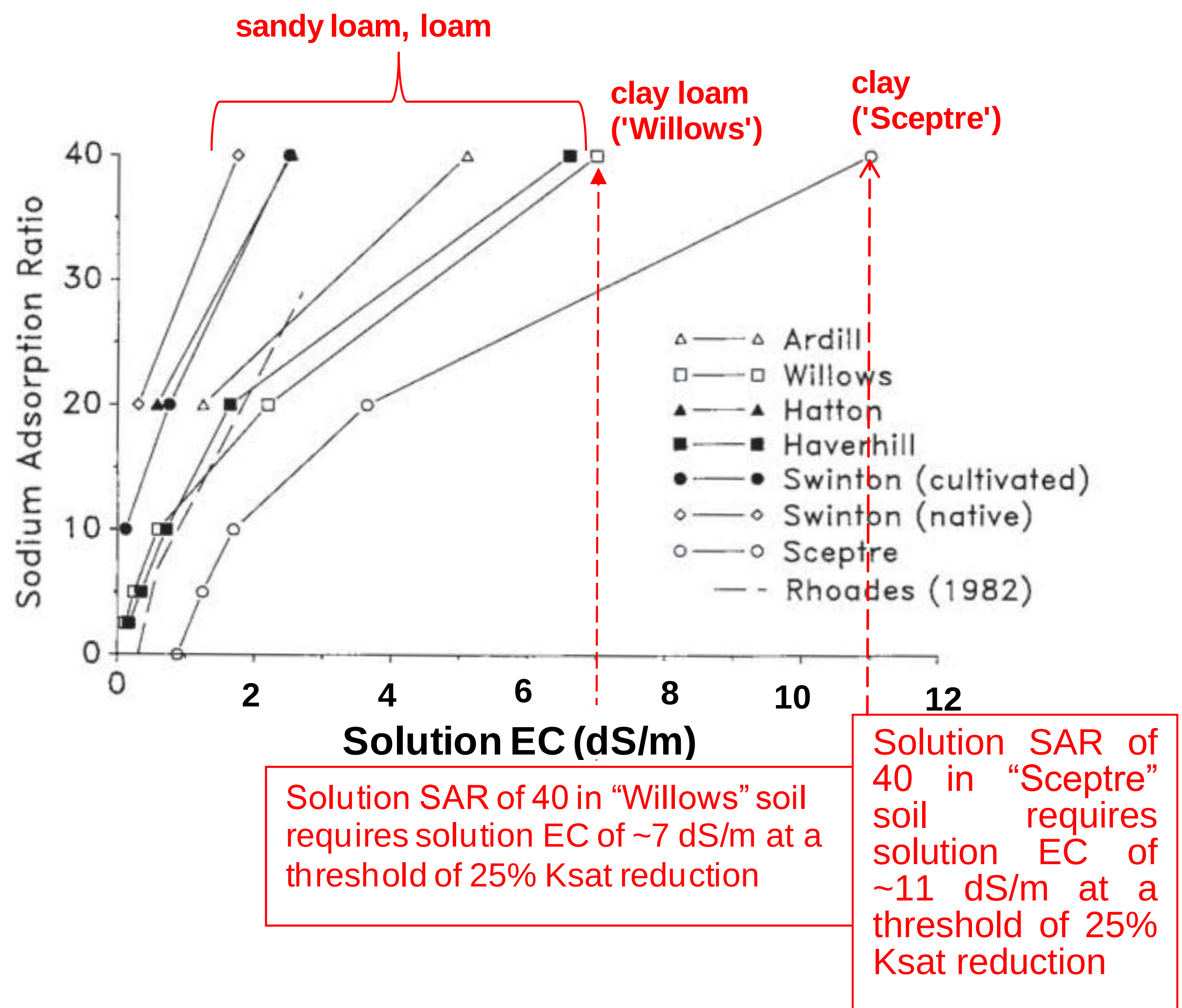
	Soil	% Clay	Texture
●	Hatton	13%	Sandy loam
●	Ardill	18%	Sandy loam
●	Swinton (cult)	17%	Loam
●	Swinton (native)	19%	Loam
●	Haverhill	21%	Loam
●	Willows	28%	Clay loam
●	Sceptre	54%	Clay

2.3 KSAT THRESHOLDS FROM LITERATURE

To determine appropriate EC/SAR combinations for irrigation water (a primary purpose from Curtin 1994c and numerous other studies from literature), it is necessary to define a 'threshold' for K_{sat} losses beyond which SAR-induced effects may be considered excessive. For irrigation water quality, this threshold has often been defined as a 25% K_{sat} reduction as evaluated by these repacked leaching column experiments. It is important to note that this 25% threshold does not necessarily imply that a 25% reduction in hydraulic conductivity in itself will cause significant degradation of root-zone (surface) soils. This threshold is intended to represent the onset of potential soil instability due to SAR effects, which when compounded by other factors present in surface soils could lead to poor infiltration, surface crusting, or hardpan. Such exacerbating factors present in surface soils include wet/dry cycles, dilution by low-EC snowmelt or rainwater, impact and shearing by rain droplets, or shearing by tillage.

Figure 2.7 shows typical threshold curves for various soils demonstrating the range of SAR and EC values for which a 25% reduction in hydraulic conductivity would be predicted (Curtin, 1994c). For Willows soil (loam/clay loam with 27.5% clay), a solution SAR of 40 thus requires a solution EC of approximately 7 dS/m (70 mmol cations/L) to remain stable according to this defined 25% threshold.

Figure 2.7. SAR and EC Threshold Curve for 25% Hydraulic Conductivity Reduction (Curtin, 1994c)



Notes: -above figure based on solution EC and SAR

-divided electrolyte concentration (mmol/L) by approximately 10 to get solution EC (dS/m)

"Threshold concentration relationships, based on the combination of solution SAR and electrolyte concentration at which a 25% reduction in hydraulic conductivity was observed. The broken line represents the guideline recommendation of Rhoades (1982)" (Curtin, 1994c).

For deeper subsoils below the root-zone, very little has been written in literature regarding suitable SAR thresholds. Compared to root-zone soils, subsoils are not exposed to the exacerbating factors of raindrop impact, direct dilution by low-EC rainwater or snowmelt, or shearing by tillage. Consequently, a threshold which allows a higher hydraulic conductivity reduction appears appropriate for subsoils. Context into potentially significant K_{sat} reductions may be obtained by evaluating natural variability in hydraulic conductivity due to factors other than SAR. For example, it is not uncommon to observe Shelby tube results (a measure vertical hydraulic conductivity) varying by two to three orders of magnitude within the same site despite having low SAR and similar lithology from location to location. Table 2.1 shows examples of such variability, taken from different depth intervals from one predominantly 'clay loam' site and one 'loam' site. In each case, hydraulic conductivity is observed to vary by more than 100-fold within a 3 m depth interval within the same borehole without apparent deleterious effects on water transport.

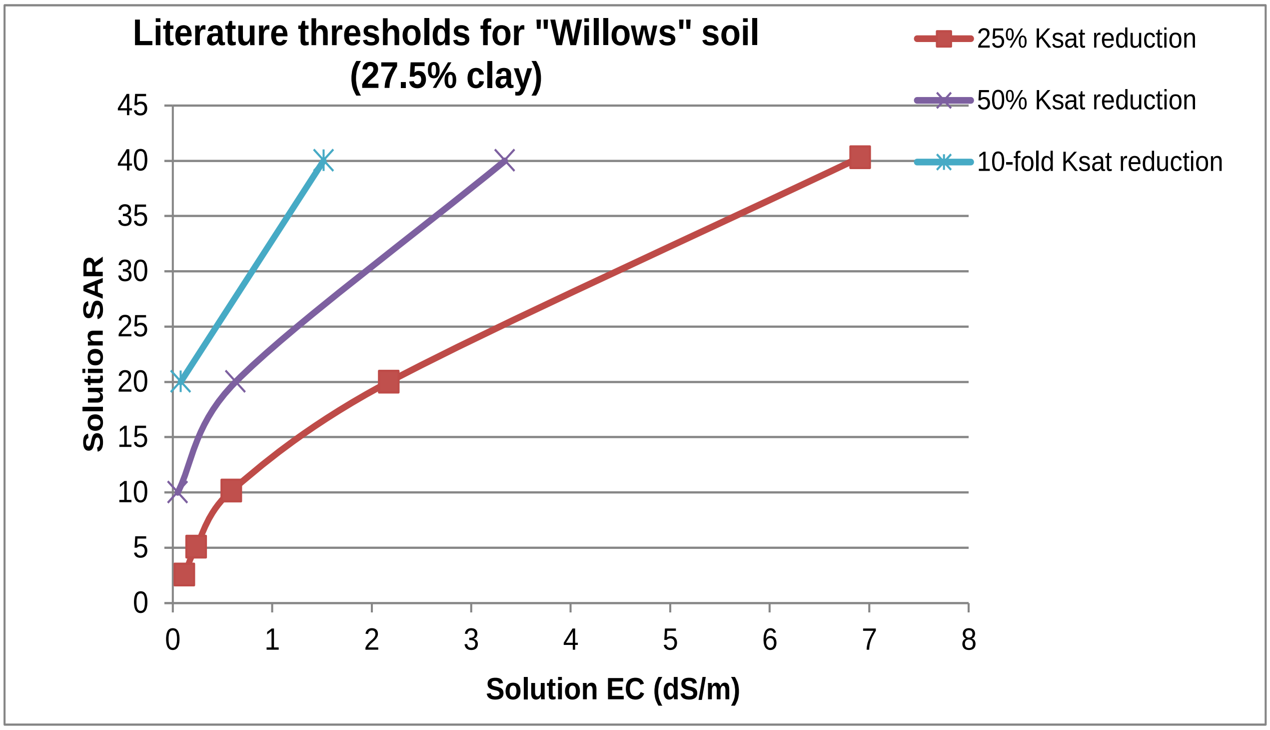
Table 2.1. Typical Variability in Hydraulic Conductivity in Soils within Example Sites

Borehole	**Depth (m bgs)**	**clay (%)**	**Texture**	**K_{sat} (m/s)**
Site A, Borehole #20	2.0 – 2.5	28	Clay loam	$4x10^{-9}$
	3.1 – 3.4	38	Clay loam	$2x10^{-10}$
	4.0 – 4.5	41	Clay loam	$1x10^{-9}$
	5.2 – 5.7	43	Clay loam	$8x10^{-11}$
Site B, Borehole #33	2.0 – 2.4	24	Loam	$1x10^{-7}$
	3.0 – 3.3	25	Loam	$1x10^{-8}$
	4.8 – 5.3	22	Loam	$2x10^{-9}$

This large natural range in subsoil K_{sat} often observed within sites suggests that factors such as soil texture, clay content, the presence of fractures and channels, and compaction can play a significant role in determining K_{sat} in the absence of SAR effects. Thus, the influence of SAR on K_{sat} should be considered one factor of many in overall water transport. For this reason plus the reduced sensitivity of subsoils to SAR effects compared to surface soils, preliminary thresholds of up to a 10-fold K_{sat} reduction (final K_{sat} of 10% of the original) may be appropriate for evaluation of site data.

As an example of comparing various thresholds, Figure 2.8 shows three thresholds for “Willows” soil based on a 25% K_{sat} reduction, 50% K_{sat} reduction, and 10-fold K_{sat} reduction. These were derived from the solution SAR/EC vs K_{sat} relationships from Curtin (1994c), and show that relatively low solutions EC values (1-7 dS/m) are required to meet these K_{sat} thresholds at a solution SAR of 40. This Willows soil (clay loam with a clay content of 28%, near the borderline of loam) is considered representative of a fairly broad range of Alberta soils and is likely to be conservative compared to coarser soils with lower clay content.

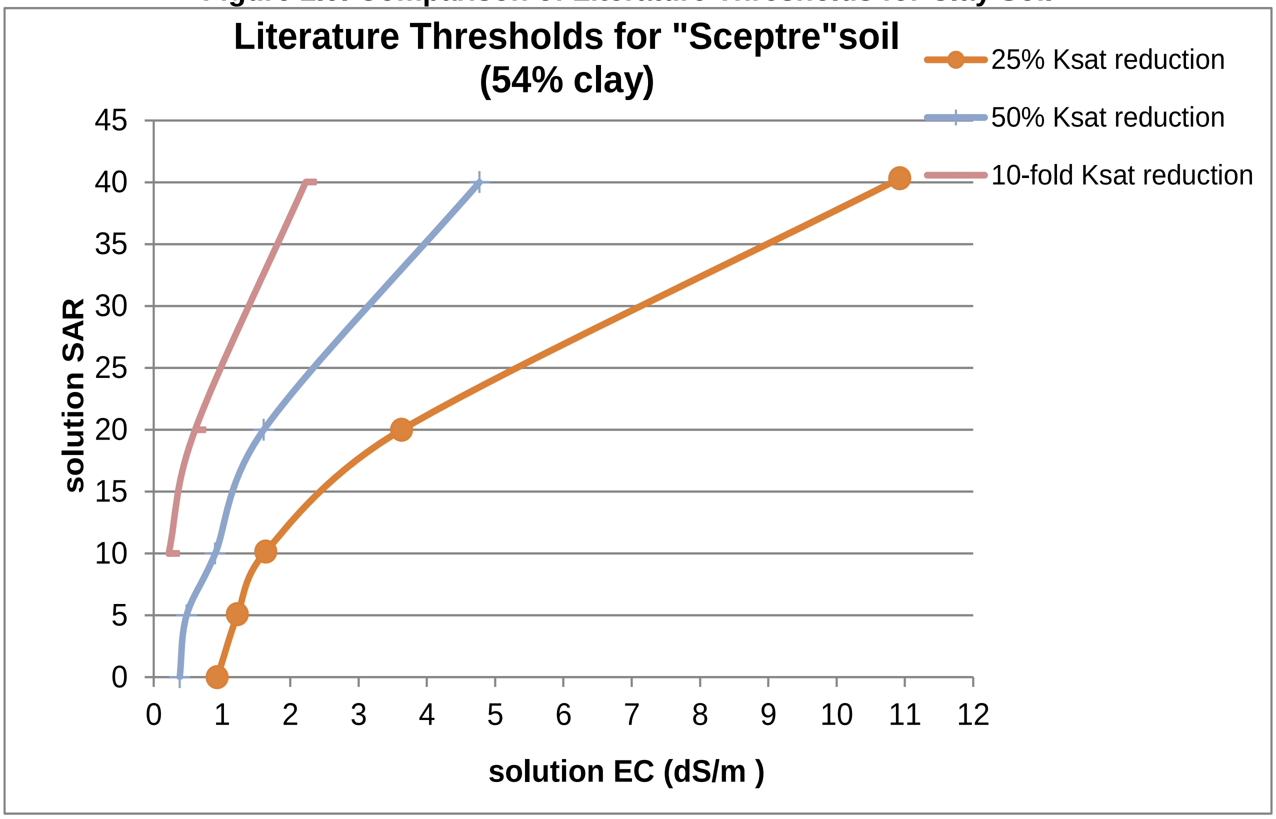
Figure 2.8. Comparison of Literature Thresholds for Loam/Clay Loam Soil



Note: data extracted from Curtin, 1994c and replotted

Figure 2.9 shows analogous thresholds for 'Sceptre' soil of 54% clay content. This figure shows that Sceptre soil is more sensitive to SAR impacts than Willows soil, likely due to the higher clay content. Higher solution EC solution values of approximately 2-11 dS/m are required to meet these three K_{sat} thresholds at a solution SAR of 40.

Figure 2.9. Comparison of Literature Thresholds for Clay Soil



Note: data extracted from Curtin, 1994c and replotted

While the majority of data from literature regarding thresholds for irrigation water are on a solution basis, SAR data from impacted sites tends to be on a soil (saturated paste) basis. Comparing and converting between these two measures is important for assessing potential SAR risk and developing SAR soil guidelines, and is evaluated further in later sections.

3 LEACHING COLUMN EXPERIMENT METHODOLOGY

3.1 APPARATUS

One method of examining SAR effects and the effects on hydraulic conductivity is through the use of leaching experiments. To perform these experiments, field soils and cores were collected from a variety of sites with varying soil texture and sulfate concentrations. Field cores were often collected in clear plastic tubes to allow easier inspection of soil type and sample integrity, though some samples were also collected in traditional metal Shelby tubes. The soils thus collected ranged from dry, coarse, light-colored sandy soils to dark, saturated clayey soils. Additional details and pictures of the experimental setup can be found in Equilibrium (2011) and are briefly summarized below.

Samples without apparent channels could be tested as ‘undisturbed’ cores in customized shelby-tube permeameters (leaching columns). Other cores with significant voids or channels were emptied, homogenized, dried and ground, and sieved through #10 (2 mm) mesh. These soil samples can then be tested as ‘repacked’ samples using one or more layers of soil in clear permeameters.

In general, the benefits of repacked soil include greater soil homogeneity combined with the ability to do multiple replicates or tests on the same soil provided sufficient soil quantities are available for testing. Potential drawbacks include a disruption of the natural soil structure which is likely altered during the grinding and screening stages. This could affect initial hydraulic conductivity, though as described in the next sections, SAR effects may be normalized relative to the baseline conductivity to compensate for this.

3.2 CONVERSIONS BETWEEN SOLUTION SAR AND SOIL SAR

Both EC and SAR can be measured in solution or in soil, with the values reported for EC/SAR curves from leaching column experiments representing inlet leaching solution concentrations. Given sufficient time, the outlet concentrations will approach the inlet concentrations and the column will reach a steady-state in terms of chemistry. If the soil is removed from the column at this point and tested with a standard saturated paste methodology, the soil results will be strongly related to the solution leached through the column but adjusted due to the differing water content. This differing water content between saturated soil and saturated paste conditions is a function of soil texture, organic matter, compaction, and other factors related to surface area, bulk density, and porosity.

For example, if fine and coarse soils with bulk density of approximately 1.6 and 1.7 kg/L are considered (similar to Alberta Environment Subsoil Salinity Tool ‘SST’ defaults), their corresponding water contents on a saturated soil basis would be approximately 25% and 21% respectively (mass of water per mass of soil) assuming fully saturated soil. If these soils have corresponding saturation percentages of 65% and 40% respectively, the water content ratios between saturated soil and saturated paste is calculated to be approximately 2.6-fold for the fine fold and 1.9-fold for the coarse soil. If higher bulk densities are assumed without a corresponding change in saturation percentage (*e.g.*, due to soil compaction in subsoil), these ratios could range from 2-3 depending on soil texture.

Results from preliminary 2009 leaching column results generally support this 2-3 fold ratio, with the higher 3-fold ratio considered more conservative in terms of generating soil guidelines from EC/SAR solution thresholds. Solution EC values would thus be divided by approximately 3 to estimate the equilibriated saturated paste soil equivalent under the assumption that all salts are completely dissolved and non-sorbed at both water contents. Solution SAR would then be divided by the square root of 3 (approximately 1.7) to estimate saturated paste SAR due to the square-root in the definition of SAR.

As a specific example, if a leaching solution has an EC=9 and SAR=69, this would be estimated to correspond to saturated paste soil concentrations of approximately EC=3 and SAR=40 using a ratio of 3 for EC and ratio of 1.7 for SAR. If a 2-fold factor was used instead for EC, a 1.4-fold ratio would be used for SAR and soil saturated paste levels of EC=4.5 and SAR=35 would be predicted. These conversions between solution EC/SAR values and estimated soil EC/SAR values form an important bridge toward implementing leaching column results into eventual soil guidelines.

4 PREVIOUS EXPERIMENTS

Previous experiments are described in detail in Equilibrium Environmental 2011, with key aspects briefly reviewed below. These experiments consisted of "Phase 1" experiments from 2009-2010, and "Phase 2" (part a) experiments from 2010-2011.

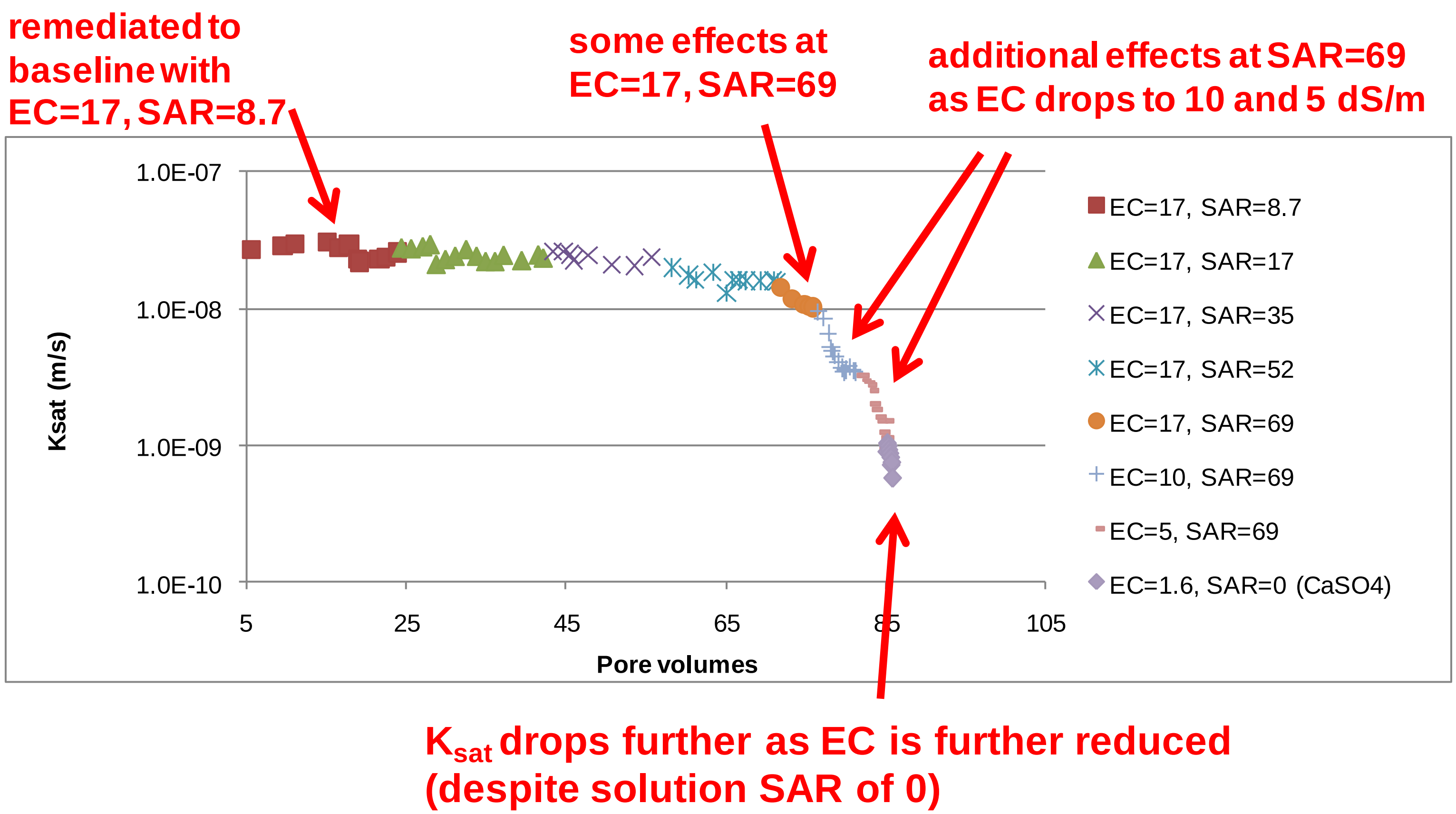
4.1 PHASE 1: 2009-2010

4.1.1 Phase 1 Overview

During the first (2009) stage of this research project, numerous preliminary leaching column experiments were performed to investigate soil EC/SAR interactions with hydraulic conductivity. This preliminary testing also functioned to refine testing methodology, evaluate the effects of soil compaction, and compare undisturbed versus repacked columns (further details provided in Equilibrium Environmental, 2010). In these experiments, soil columns (either repacked or undisturbed) were leached with solutions with various EC/SAR combinations up to a solution SAR of 40 and outlet flow rate was measured at various time intervals. Hydraulic conductivity was then calculated according to standard procedures using Darcy's Law (Aringhieri, 1994). Similar to Curtin (1994c). Several experiments were performed whereby a solution with high solution SAR (such as SAR=40) was first leached at sufficiently high EC (*e.g.*, 80 dS/m) to allow evaluation of baseline flow properties. Hydraulic conductivity losses at the various steps were then converted to a percentage of the baseline conductivity to obtain a 'relative' hydraulic conductivity.

The next Phase 1 experiments, starting in 2010, utilized methods developed in 2009 and expanded on the earlier results by testing additional soil types and solution SAR values up to 69. This is higher than the previous maximum of solution SAR=40. With a solution SAR of 69 estimated to correspond to a saturated paste soil SAR of approximately 40. Figure 3.6 shows one example of an experiment from this SAR=69 series with decreasing EC from a baseline of 17 to 1.6 dS/m. Results indicate a minor, gradual decline in K_{sat} as SAR is increased from 8.7 to 52 at EC=17 dS/m and additional effects at SAR=69, although the overall effect remains lower than one order-of-magnitude. Additional, stronger effects occur as EC is dropped to 10 and 5 dS/m at SAR=69, resulting in a greater than an order-of-magnitude K_{sat} loss from baseline. The first six leaching experiments for the SAR=69 series can be found in the Appendix, labeled with the IDs: JM1.1, JM2.1, L3.1, L4.1, L5.1, and L6.1. A comprehensive list of Phase 1 and 2 column experiments is shown in Table 11.1.

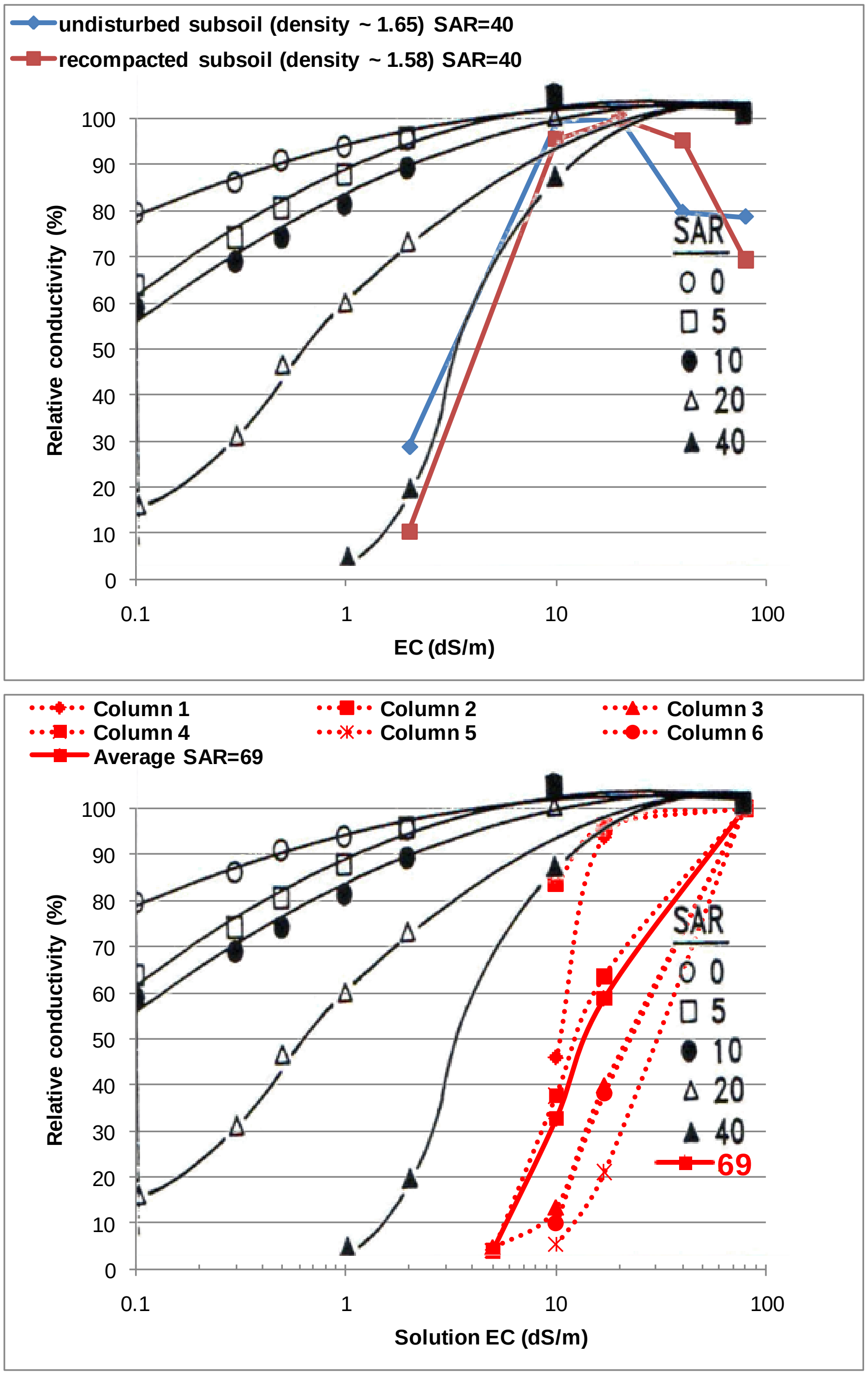
Figure 4.1. SAR=69 experiment #1



4.1.2 **Phase 1 Summary: SAR=40 and SAR=69**

Figure 4.2 shows the results of a SAR=40 series for two soil types overlain on the results from Curtin (1994c) for soil with a similar texture / clay content. Results from six of the SAR=69 experiments were also plotted in the same manner and shown overlain on these literature results for “Willows” soil (27.5% clay) in Figure 4.2. In both the SAR=40 and SAR=69 series, an overall similar behavior was observed, suggesting that the methodology used in this research can yield results comparable to previous research and that results from sources such as Curtin (1994c) may be useful in supplementing the data generated in this research project. The experimental results from Phase 1 of this project are observed to fit the overall pattern in the literature while extending them to a higher solution SAR of 69. The overall average response of the Phase 1 SAR=69 experiments are shown as a solid line, with some soils located to the right of this average (more sensitive) and some soils located to the left (less sensitive). Based on these promising results, Phase 2 was then commenced to expand on the results of Phase 1, including a further extension of SAR values up to 115.

Figure 4.2. Phase 1 results compared to literature. A) SAR=40 series and B) SAR=69 leaching column results are shown overlain on Curtin's (1994c) "Willows" curves results.



4.2 PHASE 2A: 2010-2011

Phase 2 experiments (now referred to as Phase 2a) were described in detail in Equilibrium Environmental 2011. Results from the Phase 1 SAR=69 series were expanded in Phase 2a by investigating several additional changes including:

- higher SAR values (up to solution SAR=115)
- lower SAR values (additional tests for solution SAR=10, 20, and 40)
- low conductivity soils
- coarse / sandy soils

Examples from Phase 2A experiments from each of the above categories are provided in Equilibrium 2011, with a full set of the leaching column results also provided in the Appendix of this document.

5 PHASE 2B EXPERIMENTS: 2011 - 2012

Phase 2A described in the previous section was expanded in 2011 to 2012 by investigating additional soil samples from a broader geographic area across Alberta. Soils and EC/SAR combinations investigated are outlined below, including a range of organic / peat soils which may behave significantly differently from mineral soils.

- SAR values ranging from 10 to >100
- Additional low conductivity soils with high clay content
- Additional coarse / sandy soils
- Organic / peat soils

These different aspects of Phase 2 are described further in sections 5.1-5.6 and a selection of the 2011 experiments are shown. A comprehensive list of Phase 1 and 2 column experiments is shown in Table 11.1, and graphs of their results can be found in the Appendix. Each column experiment was assigned a unique ID based on their geographic origin. Refer to Equilibrium Environmental 2011 for examples of Phase 2 work from 2010.

5.1 SAR=115 SERIES

Several columns were tested in a similar manner as the Phase 1 SAR=69 series, but with a maximum SAR of 115 instead. These columns were typically baselined with a sufficiently high EC (*e.g.*, 80 dS/m) to ensure no significant effects due to SAR=115. In some cases, additional assurance of baseline conditions was also provided by a pre-baselining step which involved pre-leaching the soil with EC=2, SAR=1 (also considered to result in insignificant SAR effects based on Curtin, 1994c).

5.1.1 SAR=115 example #1 (ID: HA8.5)

One example of a SAR=115 experiment is shown in Figure 5.1 for a clay loam soil. At an EC=80, SAR=115 baseline, this soil was largely protected from SAR effects due to the high EC. However, as EC dropped abruptly from 80 to 2 dS/m, a K_{sat} loss of nearly 2 orders-of-magnitude was observed, resulting in a final hydraulic conductivity approaching $5x10^{-10}$ m/s.

5.1.2 SAR=115 example #2 (ID: HA16.2)

Compared to an EC=80, SAR=115 baseline, this soil maintained essentially the same K_{sat} conditions at SAR = 115 even as EC was reduced to 2 dS/m (Figure 5.2). Upon introduction of a harsh EC=1, NaCl solution, relatively modest K_{sat} reductions were observed. The final resulting hydraulic conductivity was reduced to approximately $2x10^{-10}$ m/s compared to the initial baseline of ~$5x10^{-10}$ m/s. Changes such as this that result in less-than-an-order-of-magnitude fold changes may be common in clayey soils which have been observed to have difficulty achieving hydraulic conductivities below 10^{-10} m/s, regardless of the influence of SAR. This effect is considered in more detail in Equilibrium Environmental 2011.

5.1.3 SAR=115 example #3 (ID: TR11.3)

Figure 5.3 shows an additional SAR=115 experiment. Achieving an initial baseline at about $2x10^{-8}$ m/s at EC=80 and SAR=115, this soil was resilient to even major reductions in EC. As EC was reduced by 40-fold to 2 dS/m, the resulting minor drop in hydraulic conductivity was barely distinguishable, stabilizing at ~$1x10^{-8}$ m/s. When EC was dropped to 1 dS/m and SAR increased to >100 (harsh NaCl solution), K_{sat} reduced to a minimum measurement of 2.4 $x10^{-9}$ m/s. This represents a near-10-fold reduction in K_{sat}, but at EC/SAR levels not representative of typical Site conditions. This represents a near-10-fold reduction in K_{sat}, but at EC/SAR levels not representative of typical site conditions. Thus, the general lack of response to changes in over typical EC and SAR ranges implies a relative insensitivity to SAR. Similar to the previous example, this suggests that it might be difficult for clayey soils to reach hydraulic conductivities below 10^{-10} m/s, regardless of the influence of SAR.

5.1.4 SAR=115 example #4 (ID: HA1.4)

Figure 5.4 show an additional SAR=115 experiment with a fast initial hydraulic conductivity of approximately $8x10^{-7}$ m/s (baselined with EC=80, SAR=115). As the EC was gradually reduced 40-fold to 2 dS/m, hydraulic conductivity remained unaffected. Changes such as this that result in less-than-an-order-of-magnitude fold changes may be common in clayey soils which have been observed to have difficulty achieving hydraulic conductivities below 10^{-10} m/s, regardless of the influence of SAR. This effect is considered in more detail in Equilibrium Environmental 2011.

Figure 5.1. SAR=115 example #1 (ID: HA8.5)

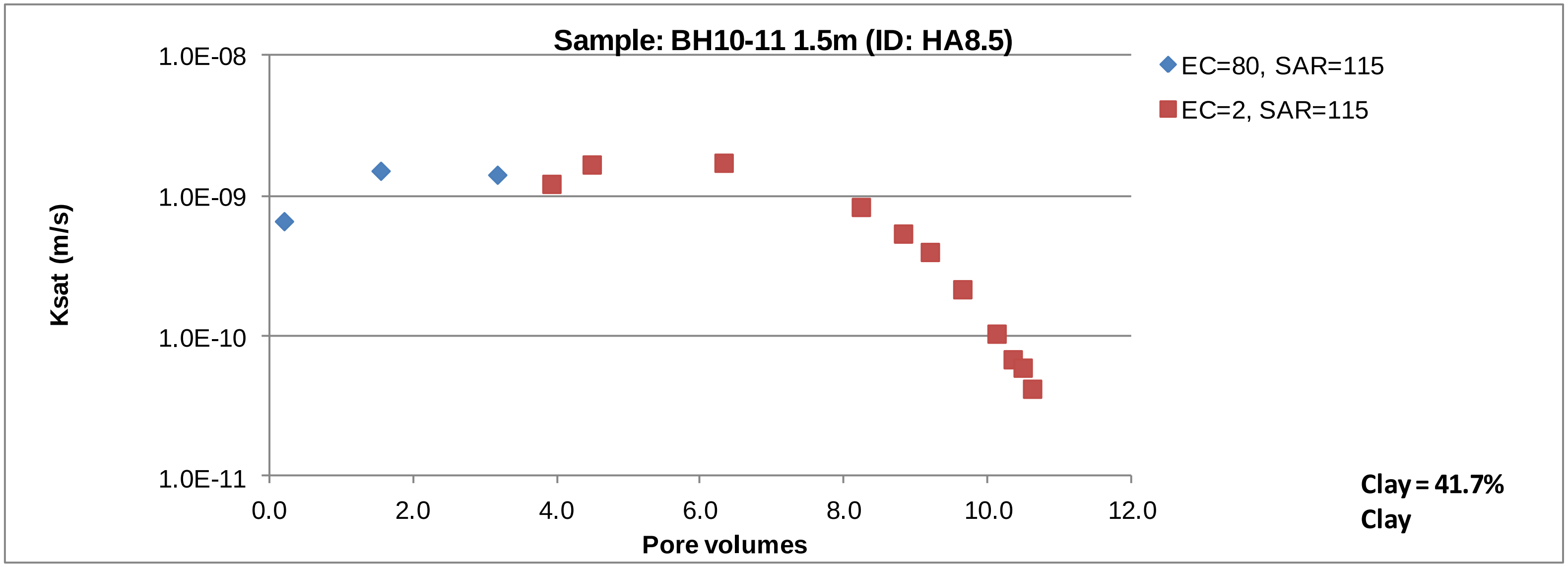


Figure 5.2. SAR=115 example #2 (ID: HA16.2)

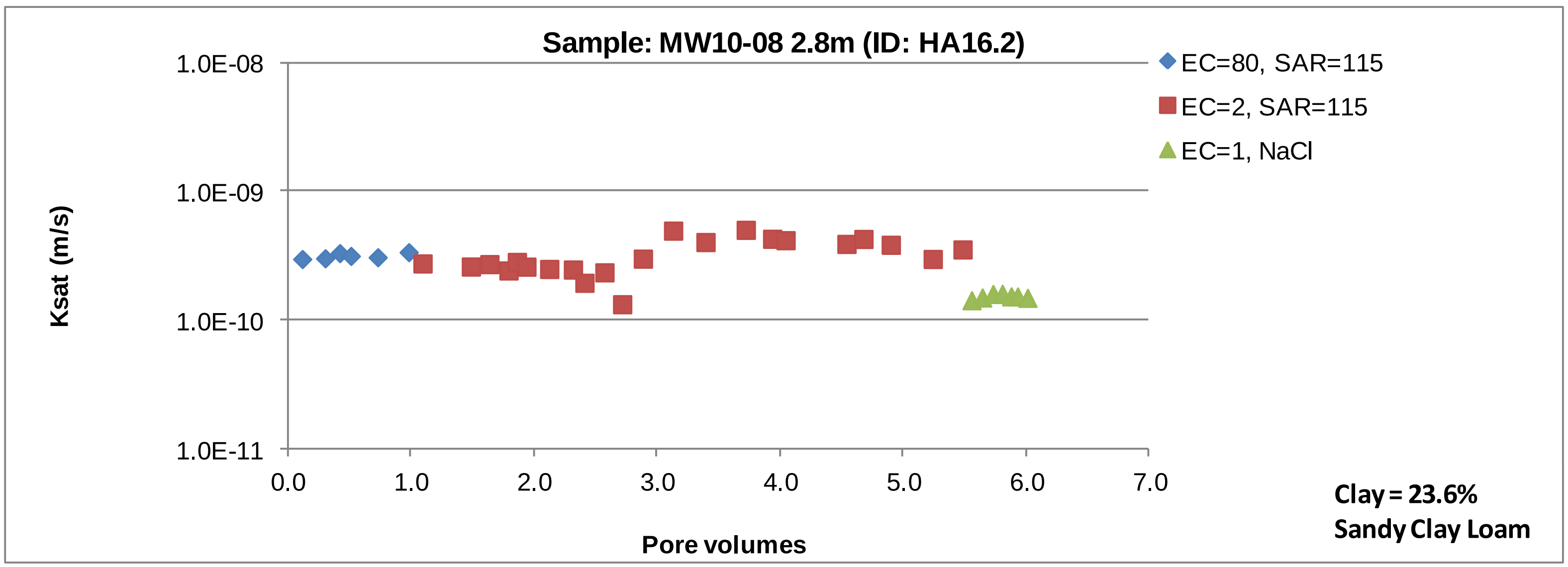


Figure 5.3. SAR=115 example #3 (ID: TR11.3)

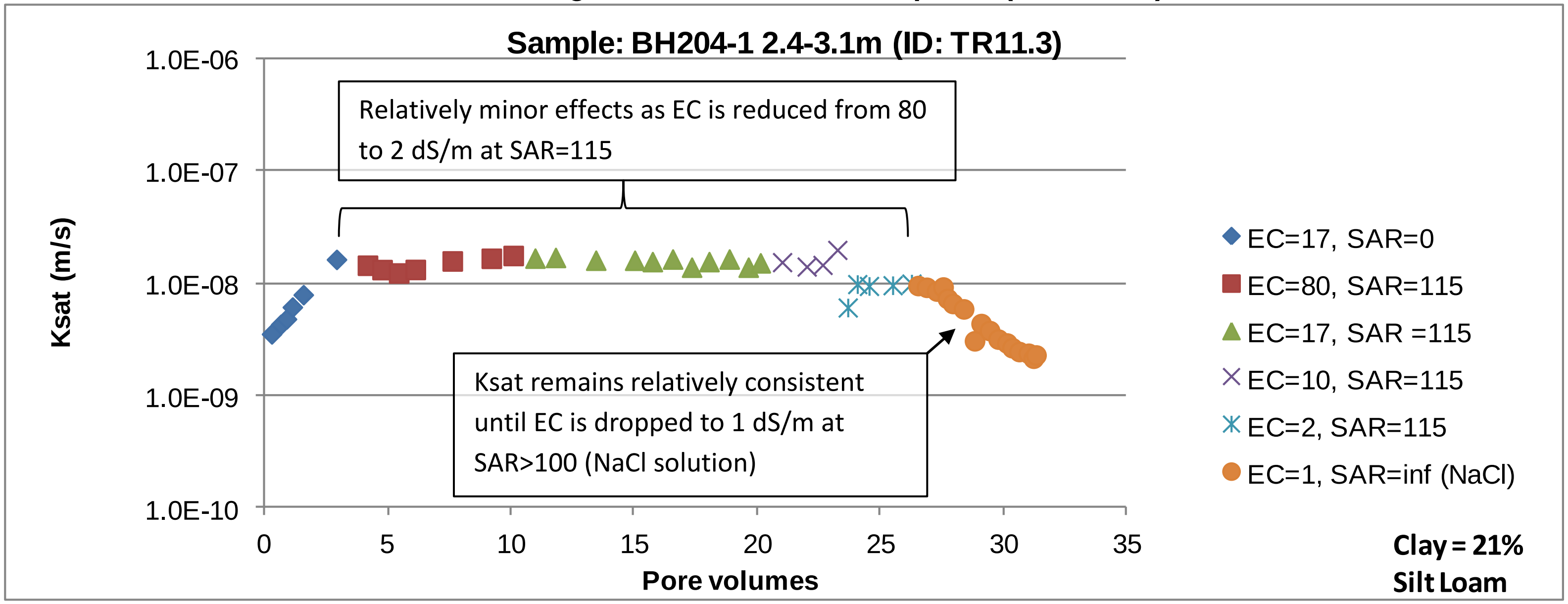
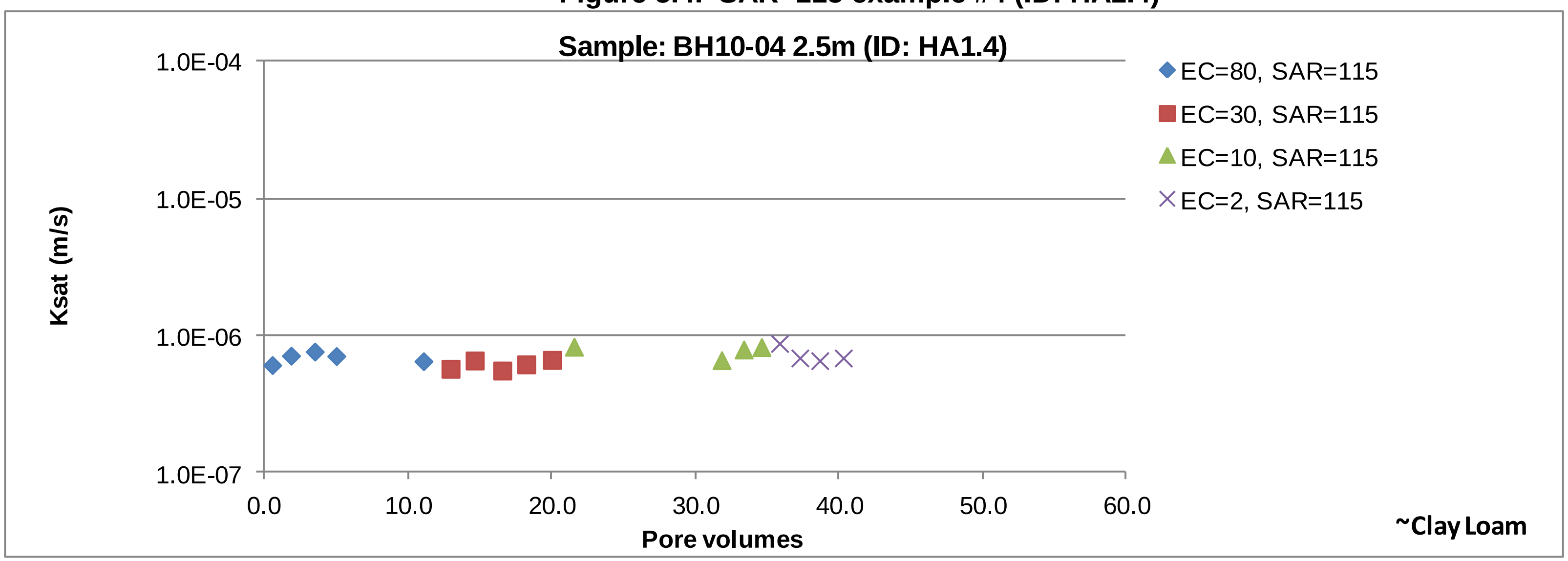


Figure 5.4. SAR=115 example #4 (ID: HA1.4)



5.2 LOWER SAR SERIES

Compared to the Phase 1 SAR=69 series, it is also relevant to test lower SAR values such as 40, 20, or 10 to provide additional overlap with literature results such as Curtin, 1994c.

5.2.1 SAR=40 example #1 (ID: QA19.4)

Figure 5.5 shows an example of a SAR=40 experiment for a fairly coarse loam / sandy loam soil. The first leaching solution of EC=80, SAR=40 resulted in a starting K_{sat} of ~2.0×10^{-8} m/s. After an initial increase to baseline at EC=10, SAR=40, there were no further reductions in K_{sat} as EC was reduced from 10 to 1 dS/m (at SAR=40). Even after increasing SAR to 100, no change in hydraulic conductivity was observed. Other than experimental variability, minimal effects were observed on K_{sat} over the wide range of EC values tested.

5.2.2 SAR=40 example #2 (ID: L4.3)

Another example of a SAR=40 experiment is shown fir a clay loam soil in Figure 5.6. From an initial K_{sat} of ~1.0×10^{-9} m/s, a gradual increase in hydraulic conductivity was observed as EC was lowered from 40 to 17 dS/m. From a peak of ~4.0×10^{-9} m/s at EC=10, SAR=40, Ksat decreased gradually with further EC reductions to 1 dS/m. The final hydraulic conductivity was similar to that achieved by the initial solution. Only minor effects on K_{sat} resulted from this experiment which further suggests that it may be difficult for clayey soils to reach hydraulic conductivities below 1.0×10^{-9} m/s, regardless of SAR.

5.2.3 SAR=40 example #3 (ID: HA5.3)

Figure 5.7 shows an example of a SAR=40 experiment in a sandy clay loam soil. The initial baseline K_{sat} of ~2.0×10^{-9} m/s was maintained while EC dropped from 80 to 17 dS/m. A minor reduction in K_{sat} was observed as EC was further reduced to 10 dS/m, but significant reductions were visible at EC=5 dS/m and continued down to EC=1 dS/m. These effects resulted in hydraulic conductivity spanning slightly more than one order-of-magnitude, resulting in a final K_{sat} of <1.0×10^{-10}

5.2.4 SAR=20 example #1 (ID: QA13.3)

An experiment from the SAR=20 series for a loam soil is shown as an example in Figure 5.8. As solution EC was reduced from an initial value of 40 down to 1 dS/m, only minor Ksat reductions (~25%) were observed from the initial value of ~5.5×10^{-8}. Once the series of SAR=20 solutions was completed, increasing the value of SAR to 100 resulted in further, albeit minor, K_{sat} reductions.

5.2.5 SAR=20 example #2 (ID: JA8.6)

Figure 5.9 shows an example of a sandy loam soil subjected to a SAR=20 experiment whereby EC is reduced from 40 to 1 dS/m at a fixed SAR of 20. A baseline K_{sat} of 3.0×10^{-8} was reached at EC=20, SAR=20, and minimal effects were observed as EC was reduced to 10 and then to 5 dS/m. Further decreases of EC to 2 and 1 dS/m resulted in modest (~25%) K_{sat} reductions, but only after increasing SAR values to >40 did K_{sat} drop markedly to $3.5x10^{-9}$.

5.2.6 **SAR=20 example #3 (ID: JA10.6)**

Figure 5.10 shows an example of a SAR=20 experiment on a clay loam soil. From an initial baseline of $8.0x10^{-9}$, a gradual decrease in hydraulic conductivity was observed over the range of EC values tested (40-1 dS/m). The final solution of EC=1, SAR=20 resulted in the lowest Ksat of ~$1.2x10^{-9}$. Overall, less than an order-of-magnitude change in hydraulic conductivity was observed, although the decrease was steady and continuous over the EC values tested.

5.2.7 **SAR=10 example #1 (ID: QA6.4)**

Figure 5.11 shows an example of a SAR=10 experiment for a sandy loam soil with low clay content. After an initial K_{sat} increase to a baseline of ~$2.0x10^{-7}$, hydraulic conductivity remained relatively stable as EC was reduced from 10 to 1 dS/m. Even upon introduction of a harsh SAR=100 (NaCl) solution, the reduction in K_{sat} was modest (~40%).

Figure 5.5. SAR=40 example #1 (ID: QA19.4)

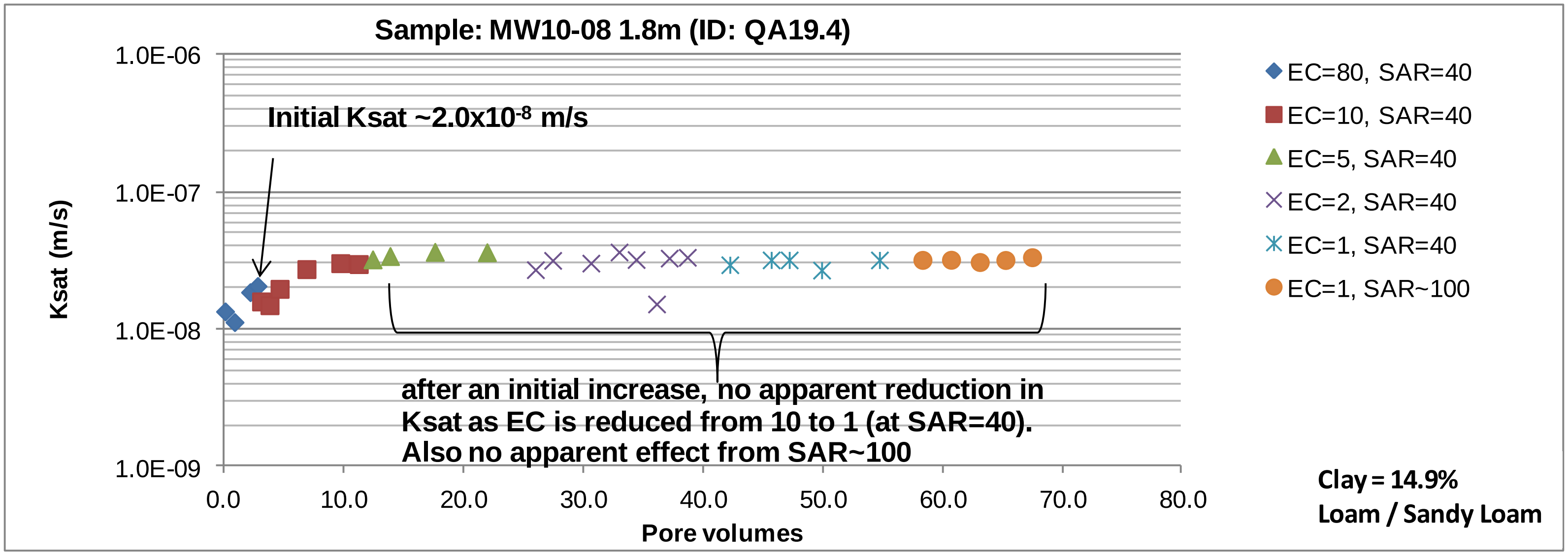


Figure 5.6. SAR=40 example #2 (ID: L4.3)

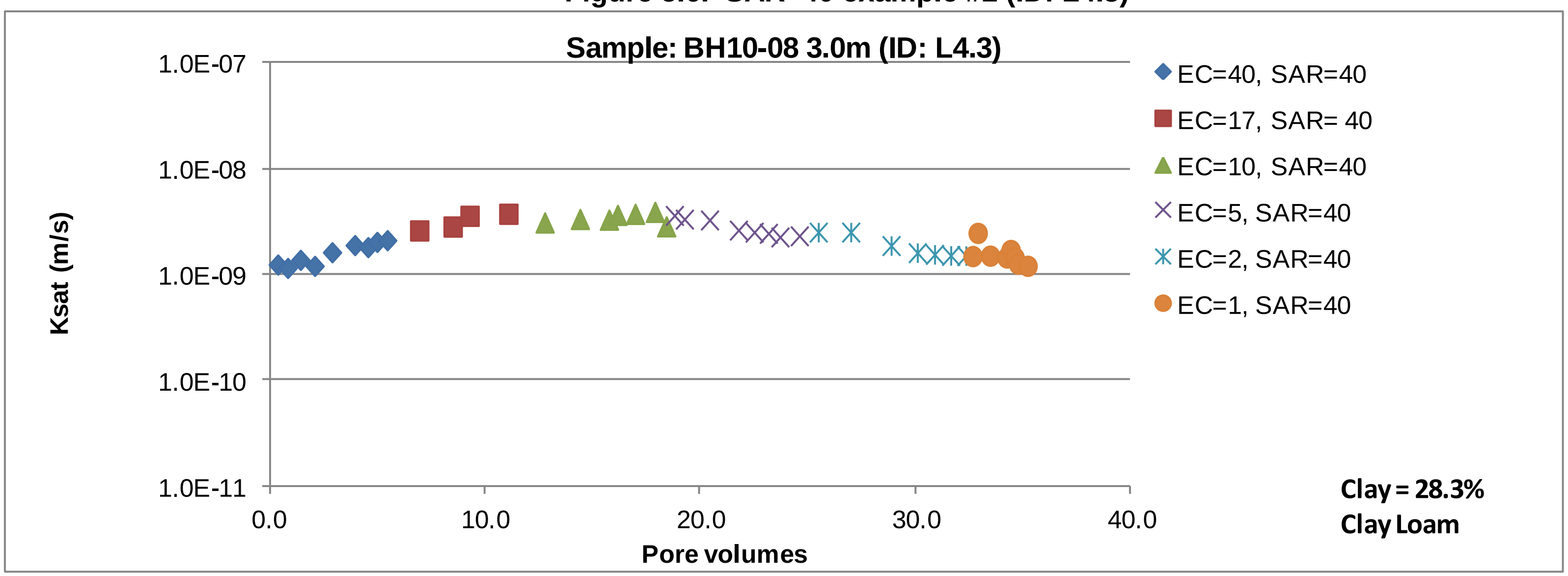


Figure 5.7. SAR=40 example #3 (ID: HA5.3)

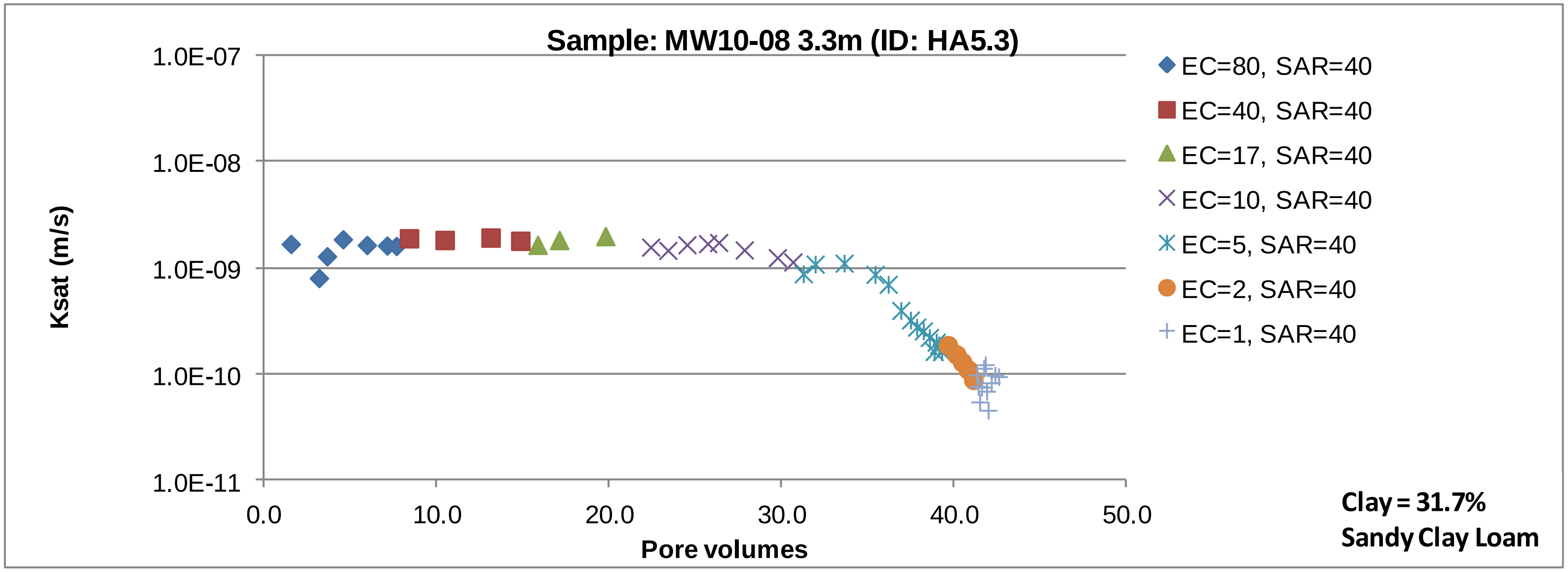


Figure 5.8. SAR=20 example #1 (ID: QA13.3)

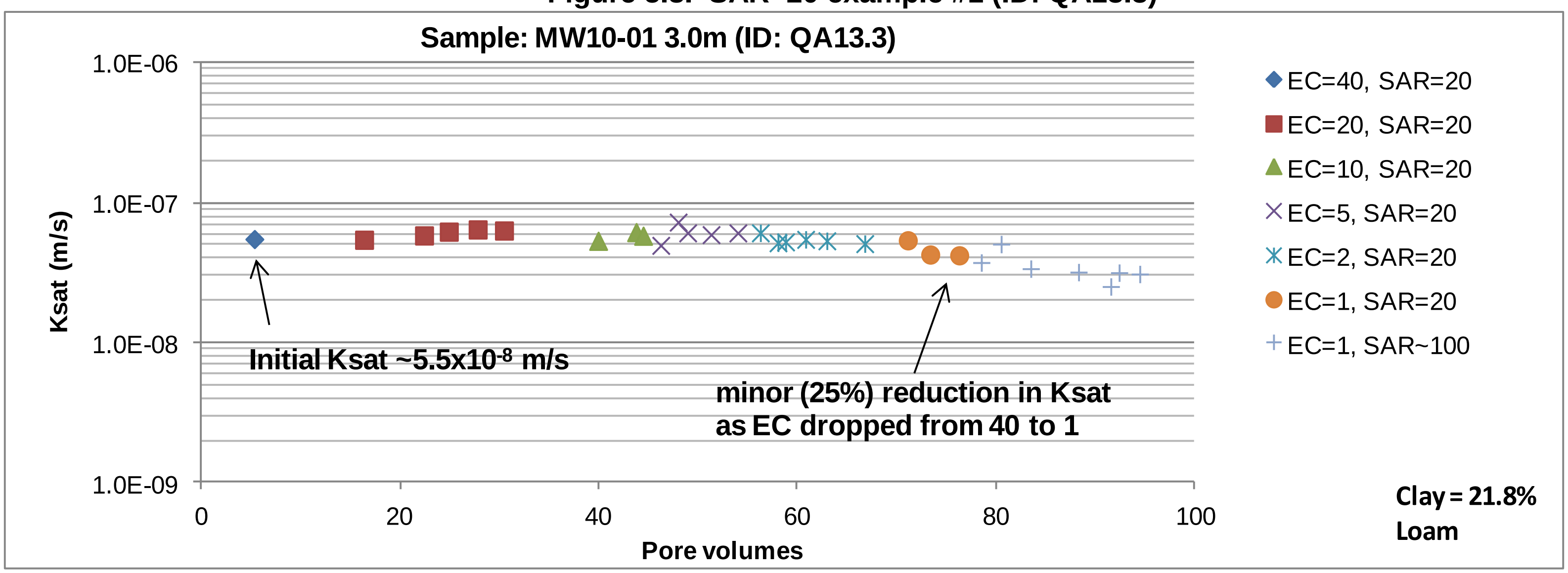


Figure 5.9. SAR=20 example #2 (ID: JA8.6)

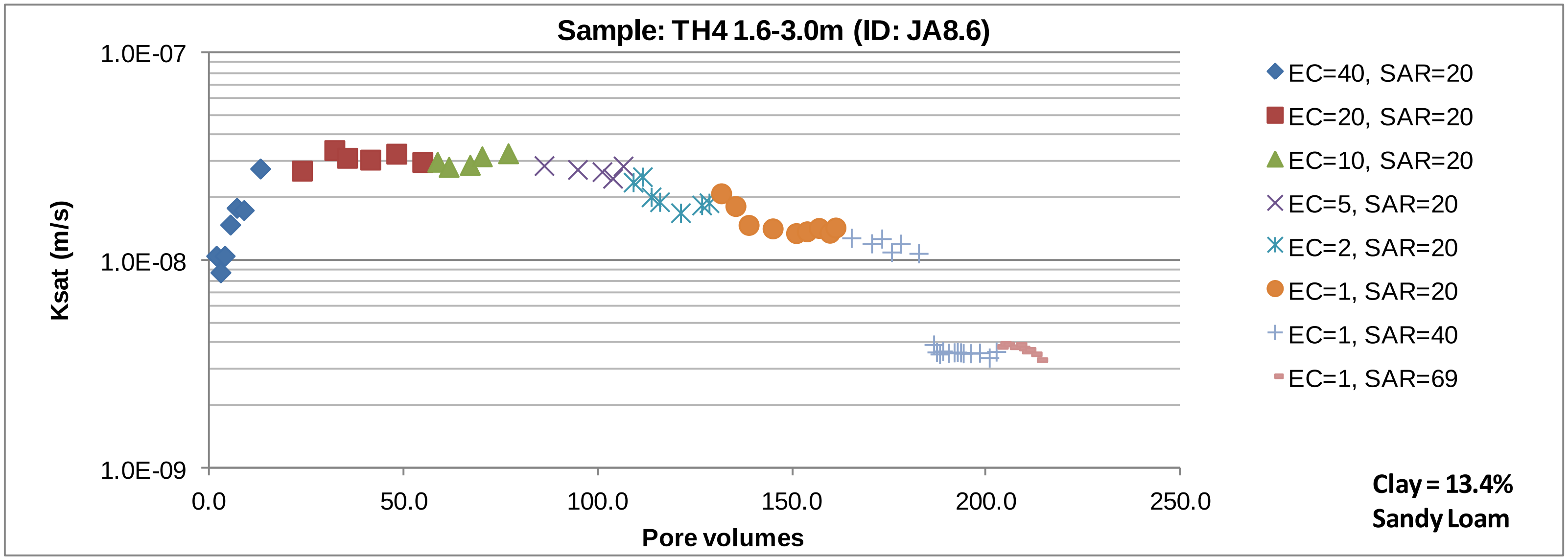


Figure 5.10. SAR=20 example #3 (ID: JA10.6)

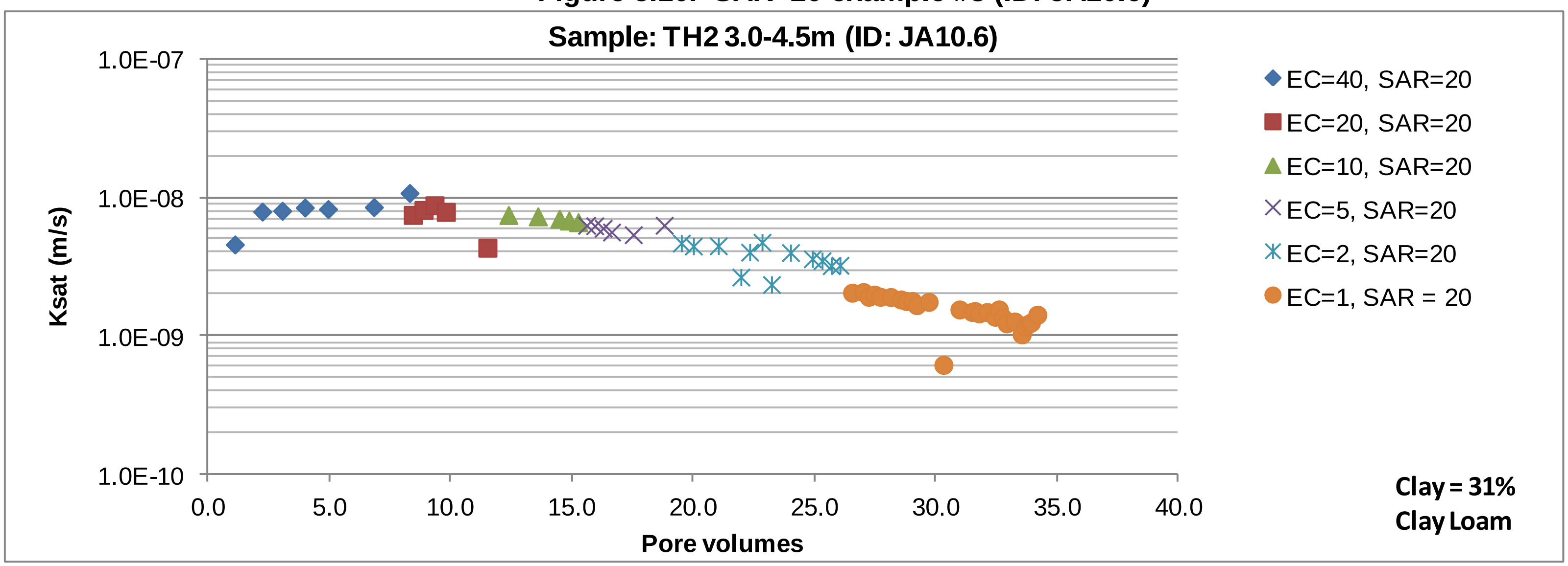
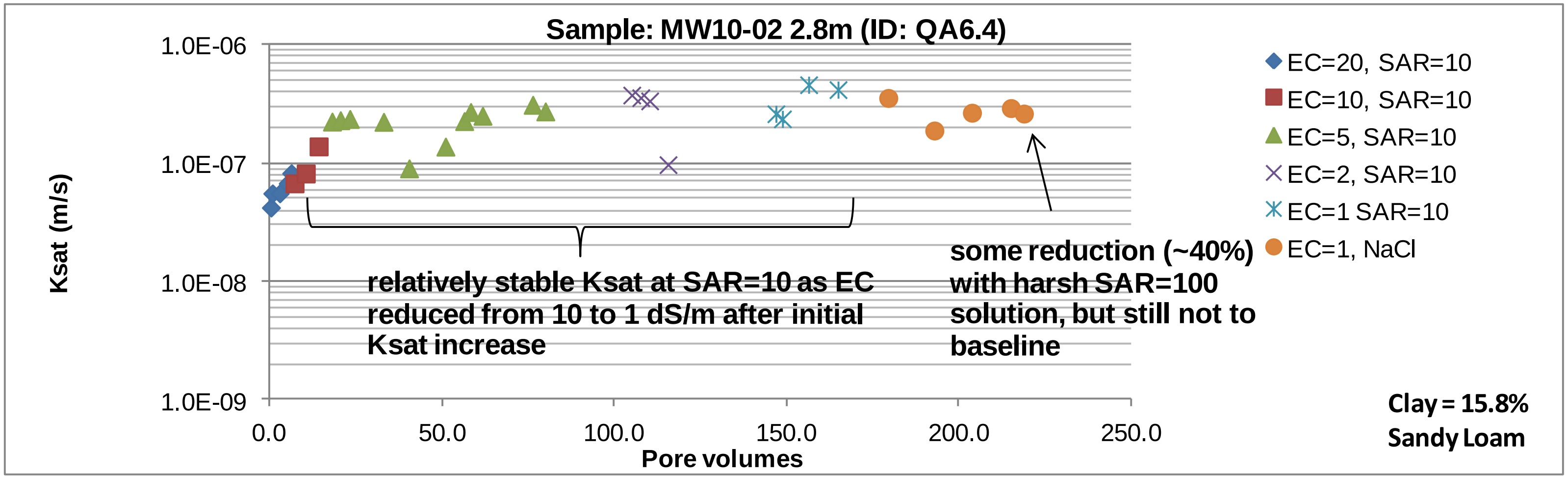


Figure 5.11. SAR=10 example #1 (ID: QA6.4)



5.3 LOW-CONDUCTIVITY SOILS

Most of the previously-tested soils had a baseline K_{sat} of between $1x10^{-7}$ and $1x10^{-9}$ m/s. Since the behavior of initially low hydraulic conductivity soils in the presence of SAR impacts has not been described in detail in literature, unimpacted cores from a field of sites near Lloydminster with particularly low K_{sat} were identified and tested for SAR sensitivity. For context, regulations in the United States typically require that compacted clay liners be below $1x10^{-9}$ m/s (Benson, 1995). In a study of thirteen clays compacted using different methods in Benson (1995), hydraulic conductivity ranged from approximately $3x10^{-10}$ to $2x10^{-11}$ m/s. Some of the soils evaluated included heavy clay marine sediment, which would thus be likely to be highly sodic. These results suggest a practical lower range for the hydraulic conductivity of clayey soils, and that SAR-induced hydraulic conductivity losses may be limited to this range as well.

In experiments to examine these potential effects, it was found that in many cases different experimental methodology was required due to the low rates of fluid flow through the columns. One useful modification was the use of 'falling head' rather than 'constant head' leaching column configurations in order to improve the accuracy of low-K_{sat} measurements. In addition, the use of thinner (3-5 cm) soil thickness to maximize flow rate in terms of pore volumes was useful compared to the 7-10 cm soil cores used for more conductive soils. Results from four such representative experiments with low hydraulic conductivity soils are described below:

5.3.1 Low conductivity soils example #1 (ID: HA17.2)

The first example of an experiment using low conductivity soils is shown in Figure 5.12. An undisturbed, unimpacted clay loam soil from near Loydminster was baselined with EC=80, SAR=69 under falling head conditions. A baseline conductivity of approximately $1x10^{-10}$ m/s was observed, likely due to the apparently tight, clayey soil with minimal visible void space or fractures. Essentially no change in K_{sat} was observed when the EC was dropped to 1 while maintaining SAR=69. This suggests that the natural state of some low K_{sat} soils may be already dispersed despite the apparent absence of SAR. The effects of soil compaction and/or shearing during the initial deposition of clays could also hypothetically cause such an effect, whereby the changes due to additional soil SAR appear to be minimal.

5.3.2 Low conductivity soils example #2 (ID: L8.3)

A similar unimpacted tight clay loam soil with low initial conductivity was also tested in example #2 (Figure 5.13). The soil was initially baselined with EC=17, SAR=8.7 and showed an initial K_{sat} of approximately $1.2x10^{-10}$ m/s but with some variability inherent in measuring low values for K_{sat}. An EC=2, SAR=115 combination resulted in negligible K_{sat} loss, as did a subsequent EC reduction to 1 dS/m while maxing out SAR. This is consistent with results from example #1 whereby a soil with initially low hydraulic conductivity appears relatively insensitive to SAR effects.

5.3.3 Low conductivity soils example #3 (ID: Z13.7)

Figure 5.14 shows a similarly tight clay loam soil with initial hydraulic conductivity around $2x10^{-10}$ m/s. No changes in K_{sat} were observed as SAR was increased from 1 to 69 while maintaining

EC=2 dS/m. This example provides further evidence for negligible SAR effects in low conductivity soils.

5.3.4 **Low conductivity soils example #4 (ID: TQ13.6)**

Another example of a leaching experiment using a low-conductivity clay loam soil is showing in Figure 5.15. An initial baseline K_{sat} of 2.0×10^{-10} m/s was reached with an EC=2, SAR=1 solution. No changes in hydraulic conductivity were observed as SAR was increased to 20, and then to 115, as EC was maintained at 2 dS/m. Overall, in this series of low-conductivity soils, no SAR effects were apparent.

Figure 5.12. Low conductivity soils example #1 (ID: HA17.2)

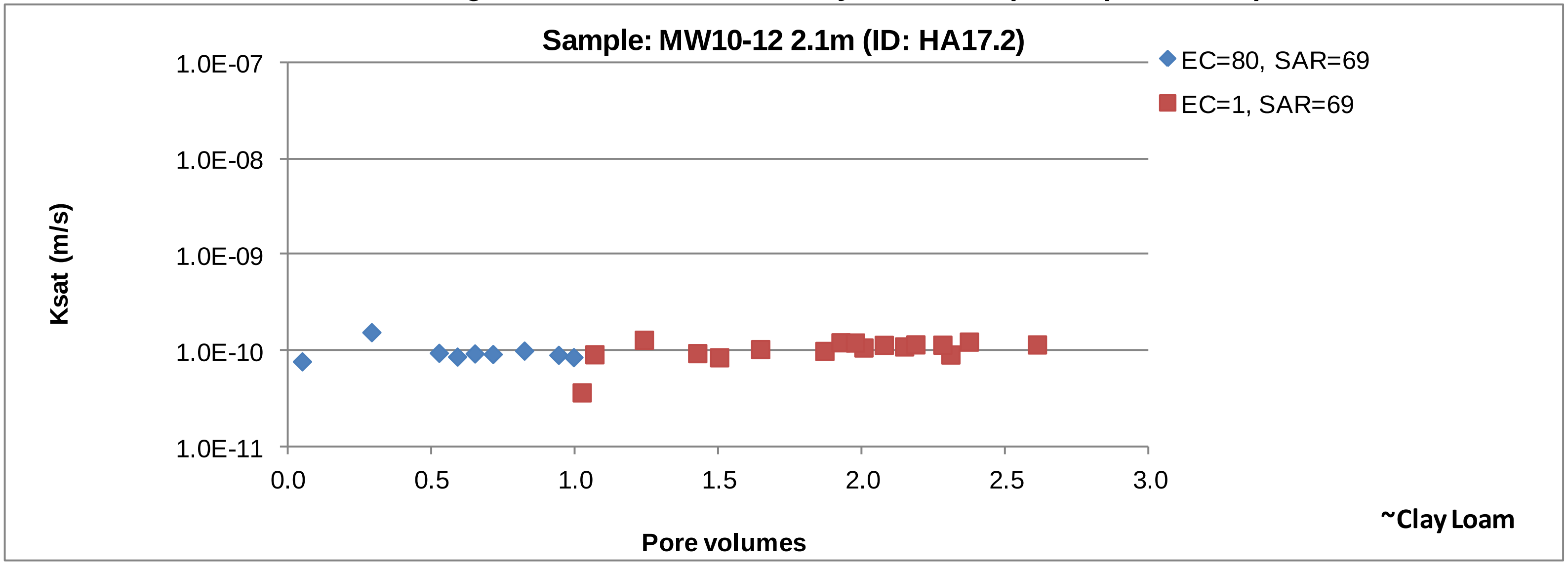


Figure 5.13. Low conductivity soils example #2 (ID: L8.3)

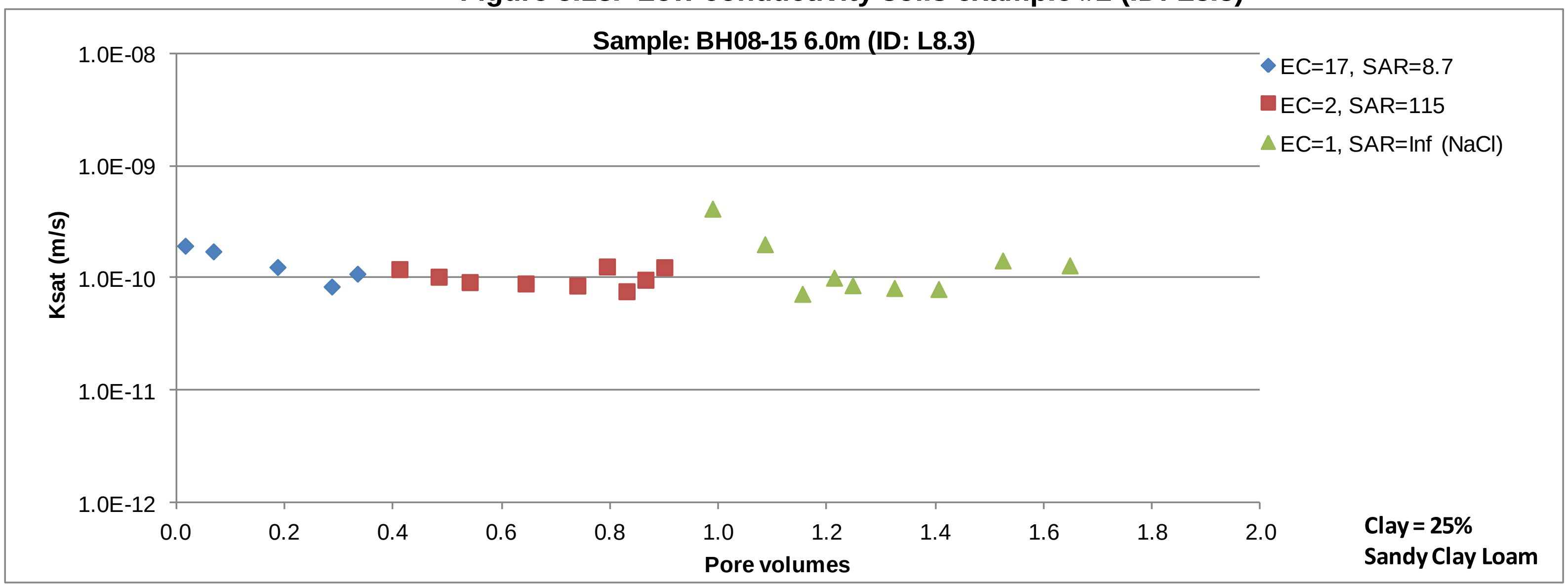


Figure 5.14. Low conductivity soils example #3 (ID: Z13.7)

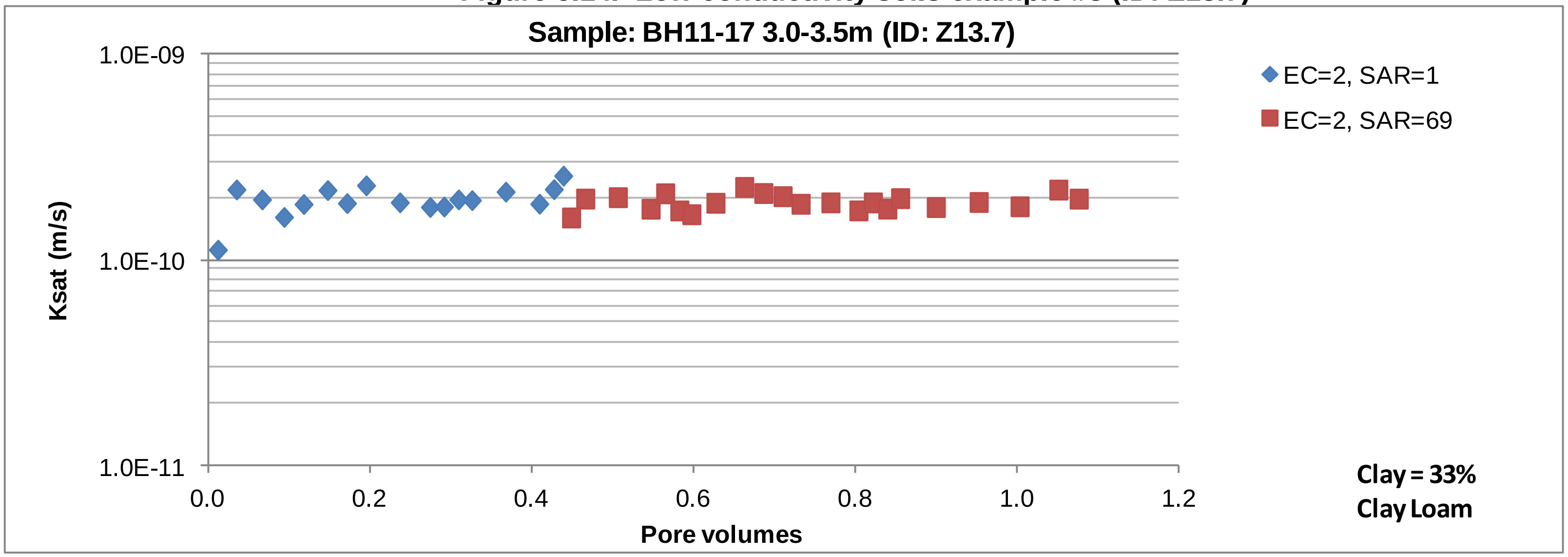
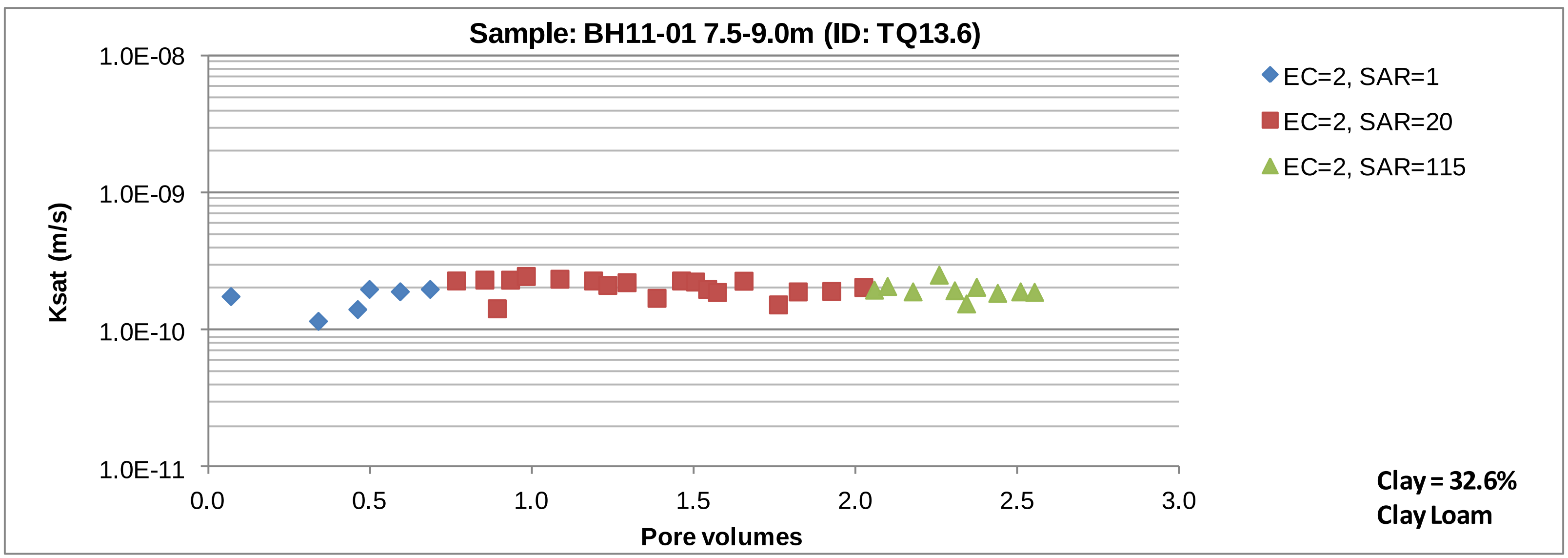


Figure 5.15. Low conductivity soils example #4 (ID: TQ13.6)



5.4 COARSE / SANDY SOILS

On the opposite end of the spectrum from the low-conductivity soils in the previous section, this section summarizes experiments performed on coarse, sandy soils. Literature results such as Curtin 1994c suggest such soils may be less sensitive than soils with higher clay content, though this considered SAR values up to a maximum of 40. Experiments on coarse soils with SAR values up to 115 are described below for a combination of repacked and undisturbed cores. K_{sat} changes were generally less than 1 order of magnitude, and support the conclusion that sandy soils may have reduced sensitivity to SAR compared to soils with higher clay content.

5.4.1 Sandy soils example #1 (ID: HA1.3)

An undisturbed core containing sandy soil (clay = 4.4%) with baseline K_{sat} near $2x10^{-5}$ m/s was cycled through a variety of EC, SAR combinations (Figure 5.16). The sole visible change in K_{sat} was induced upon switching to the EC=1, SAR=40 solution, although this only resulted in a modest ~25% K_{sat} reduction. Hydraulic conductivity returned to initial baseline levels even in spite of using an EC=1, NaCl solution (theoretically infinite SAR, practically near 100). This suggests that the influence of SAR is minimal on this soil over a practical range.

5.4.2 Sandy soils example #2 (ID: HA20.1)

The sandy loam core tested in Figure 5.17 was exposed to two different series. First, a harsh NaCl solution caused a K_{sat} reduction greater than one order of magnitude relative to the initial baseline of ~$2.5x10^{-7}$ m/s. The soil was remediated to a new, slightly lower, baseline of ~$1.0x10^{-7}$ m/s using an EC=80, SAR=69 solution. Next, solution EC values were reduced to complete the SAR=69 series. Clear decreases in hydraulic conductivity were observed for each subsequent reduction in EC.

5.4.3 Sandy soils example #3 (ID: QA4.2)

Another sandy loam soil was evaluated in Figure 5.18. An initial K_{sat} of $9.4x10^{-8}$ m/s was obtained when evaluated with a SAR=20 series (Figure 69). No apparent decreases in K_{sat} were apparent as EC was then reduced from 40 to 1 dS/m. Rather, K_{sat} increased at EC=10, stayed stable at EC=2, and then increased dramatically after a large pore volume at EC=1. This was due to the development of a visible flow channel within the core, at which point the experiment was discontinued.

5.4.4 Sandy soils example #4 (ID: QA10.3)

Figure 5.19 shows the results of a sandy loam core leached with a solution SAR=20 series (sat paste soil SAR~13). An initial K_{sat} of approximately $5.3x10^{-8}$ m/s was obtained at high EC, with no significant reductions in K_{sat} observed as solution EC was reduced from 40 to 1 dS/m. A harsh sodium chloride solution with a SAR of approximately 100 (EC=1 dS/m) was then leached to evaluate a 'worst case' scenario, resulting in a relatively minor 25% K_{sat} reduction. These results suggest a general insensitivity to SAR for this core.

5.4.5 **Sandy soils example #5 (ID: QA19.3)**

Figure 5.20 shows another experiment on a sandy loam soil using an elevated solution SAR of 40 (sat paste soil SAR ~26). The higher initial K_{sat} of $3.8x10^{-7}$ m/s compared to previous examples could be a potential indicator of inherent natural and/or experimental variability. A relatively minor K_{sat} reduction (30%) was observed as EC dropped from 80 to 2 dS/m, with limited additional reductions at lower EC and/or higher SAR. Similar to the first three examples, the undisturbed core in figure 5.20 also showed no significant changes in hydraulic conductivity over large EC/SAR ranges.

Figure 5.16. Sandy soils example #1 (ID: HA1.3)

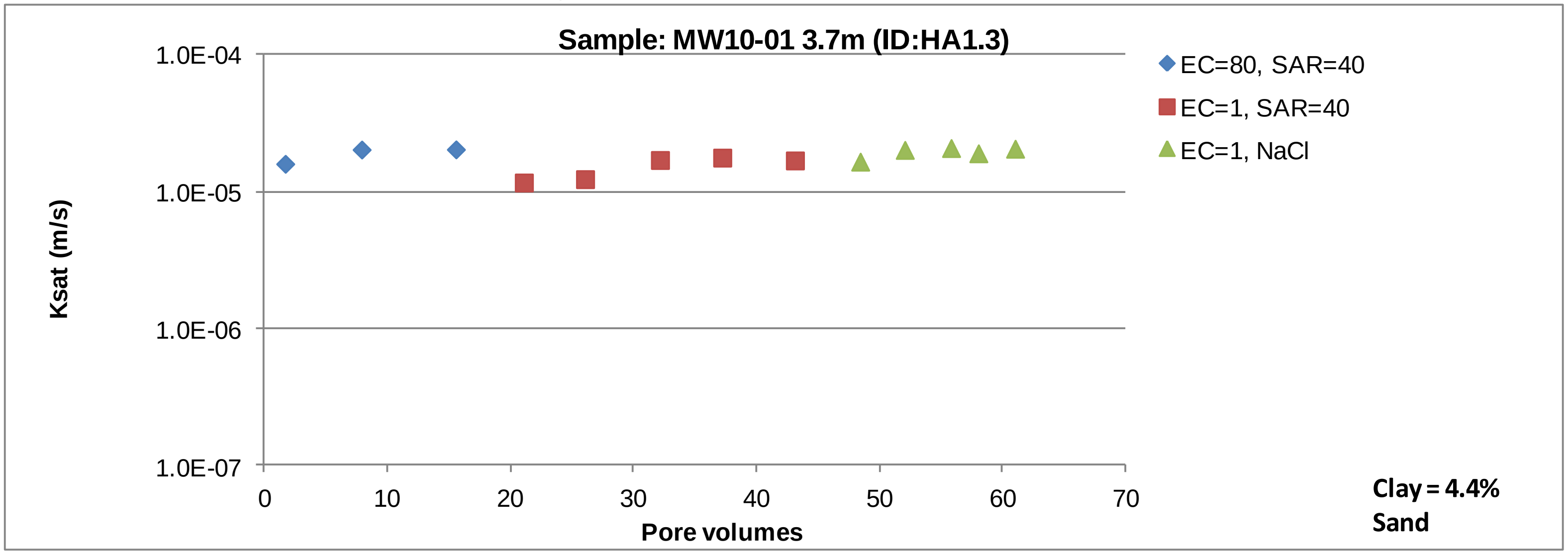


Figure 5.17. Sandy soils example #2 (ID: HA20.1)

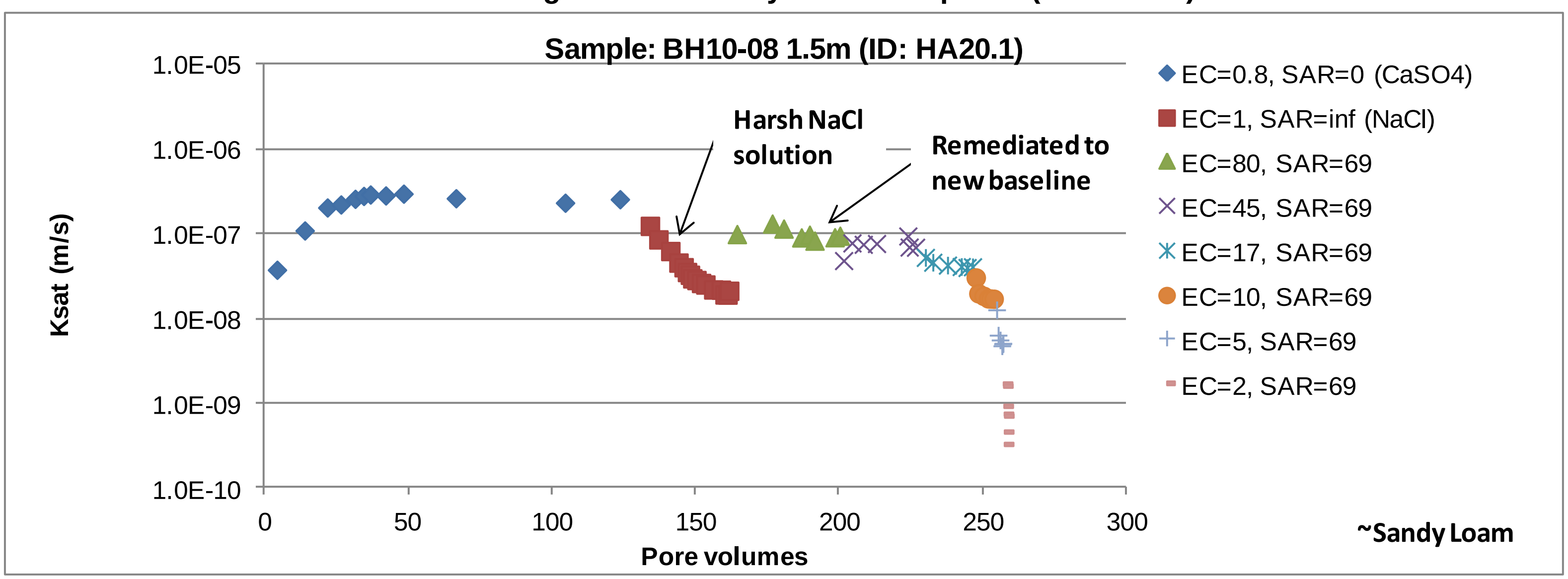


Figure 5.18. Sandy soils example #3 (ID: QA4.2)

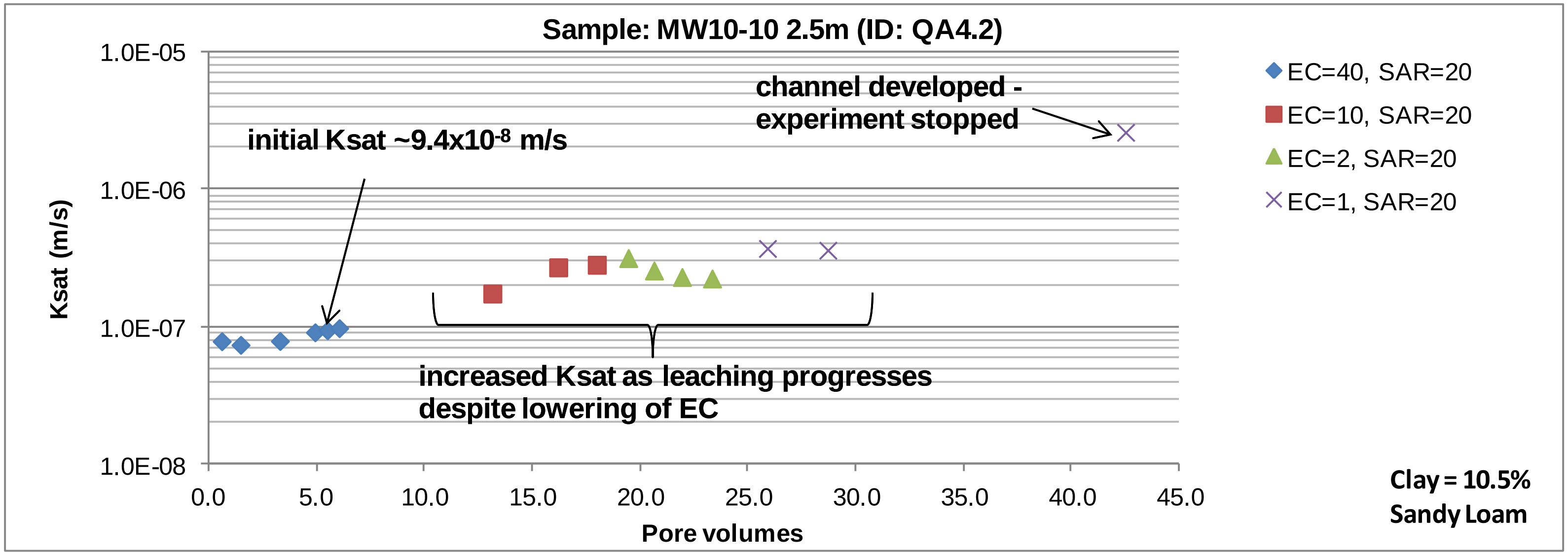


Figure 5.19. Sandy soils example #4 (ID: QA10.3)

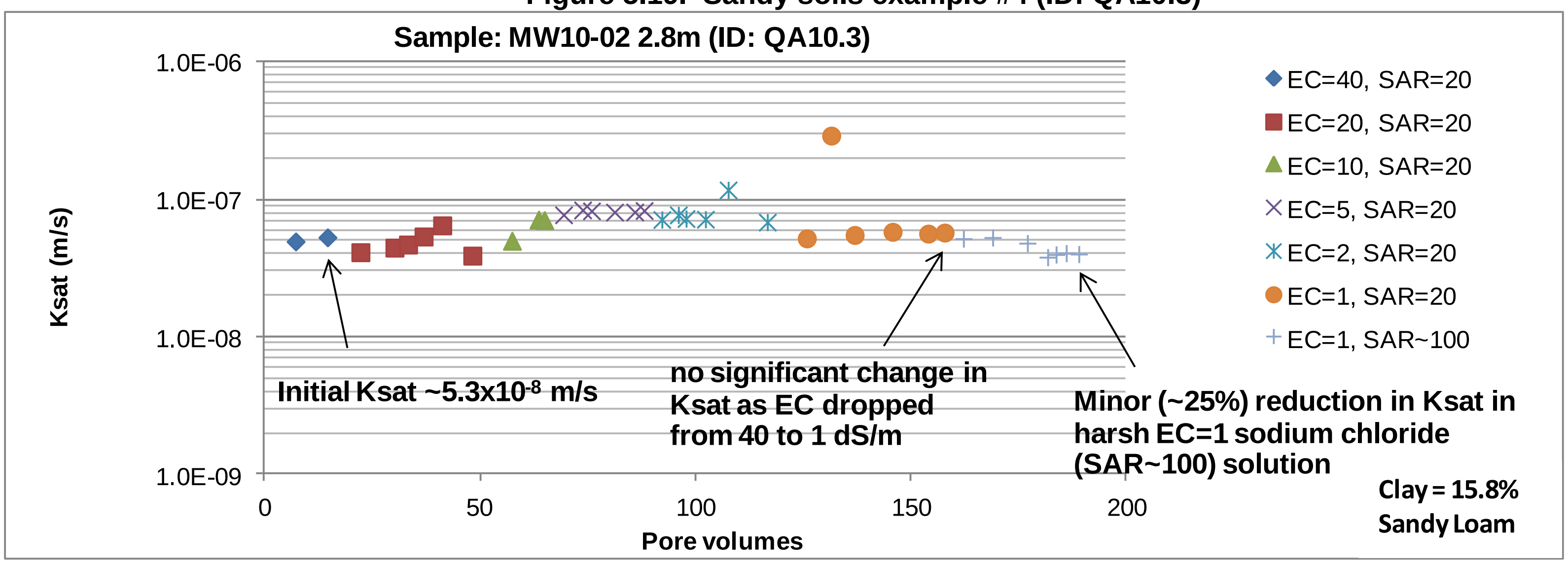
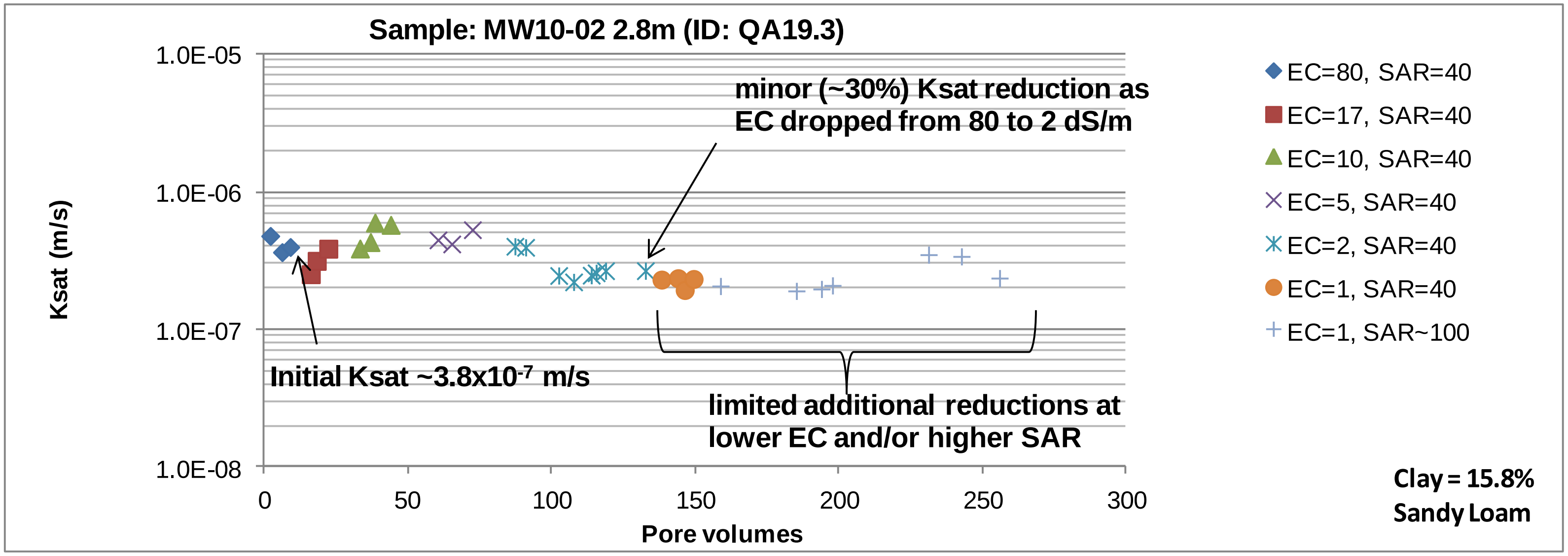


Figure 5.20. Sandy soils example #5 (ID: QA19.3)



5.5 ORGANIC / PEAT SOILS

The effects of SAR on organic peat soils were also investigated. Peat soil consists of 70 – 80% organic matter and achieves a saturation percentage of 500 – 700%. In both of the following examples, saturated paste SAR ~30+ at the completion of the experiment. Overall, preliminary results suggest minimal SAR effects on some peat soils. These results indicate that there might be little or no benefit to remediating SAR-impacted peat soils.

5.5.1 Organic/peat soils example #1 (ID: TQ12.5)

The undisturbed core of peat soil in Figure 5.21 showed no significant changes over a large EC / SAR range. After baselining with EC=2, SAR=1, minimal effects were observed upon leaching with a harsh SAR=115 solution (EC~2).

5.5.2 Organic/peat soils example #2 (ID: TQ14.5)

Similarly, the undisturbed core of peat soil in Figure 5.22 showed no significant change in hydraulic conductivity in response to a harsh SAR solution relative to baseline.

Figure 5.21. Organic/peat soils example #1 (ID: TQ12.5)

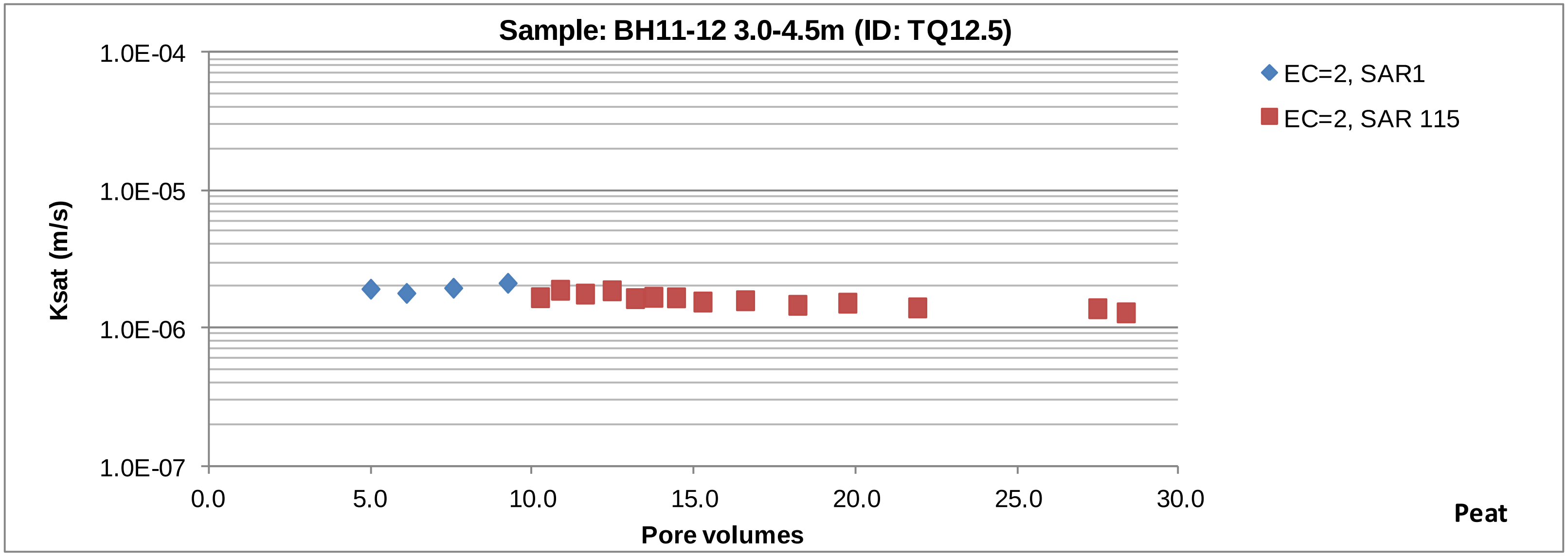
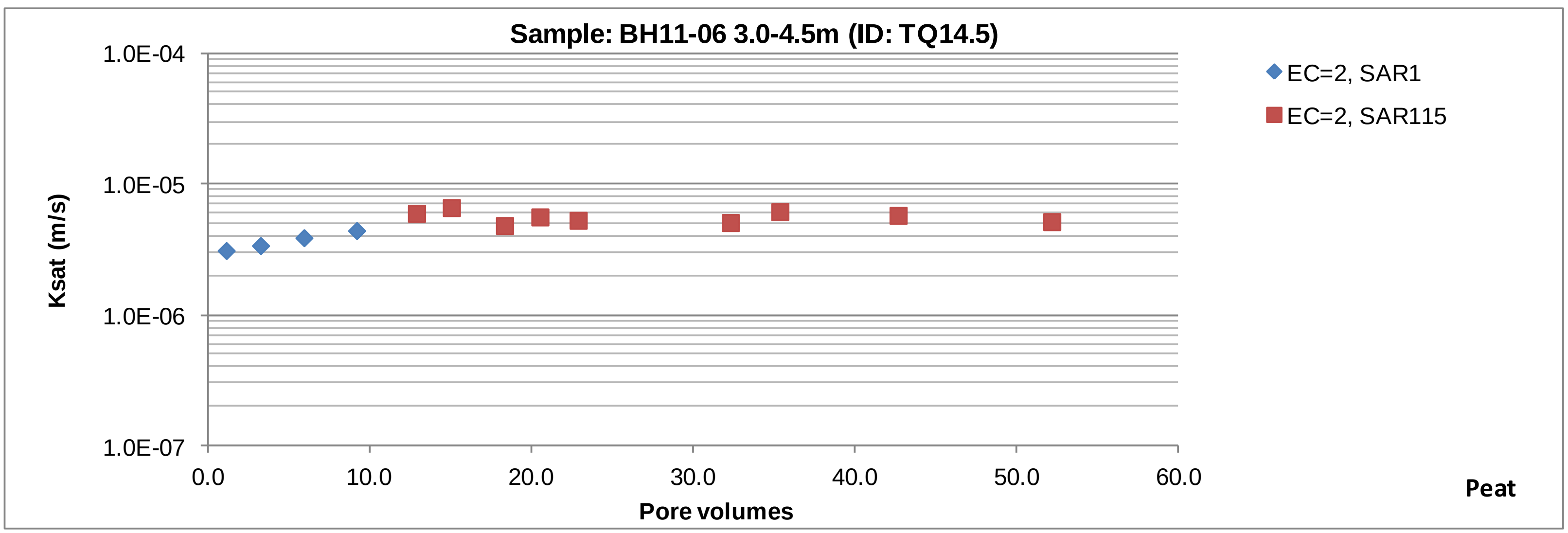


Figure 5.22. Organic/peat soils example #2 (ID: TQ14.5)

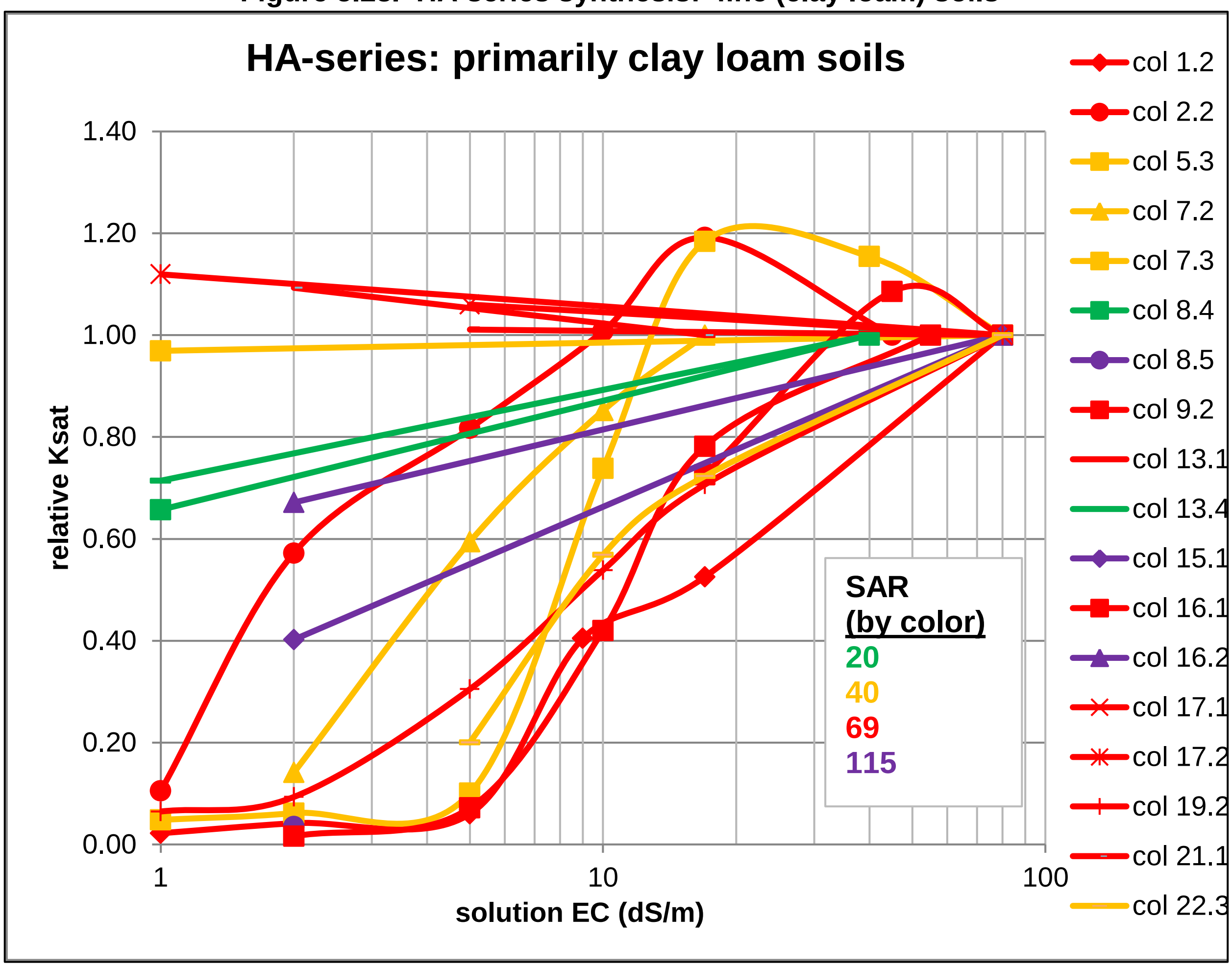


5.6 SYNTHESIS OF LEACHING COLUMN EXPERIMENTS

The large number of column experiments performed in 2011-2012 can be analyzed in a number of different ways, including syntheses by soil type, site geographic location, initial hydraulic conductivity, SAR series tested, and other factors. This section shows some example methods for synthesizing leaching column experiments depending on the factors desired to study.

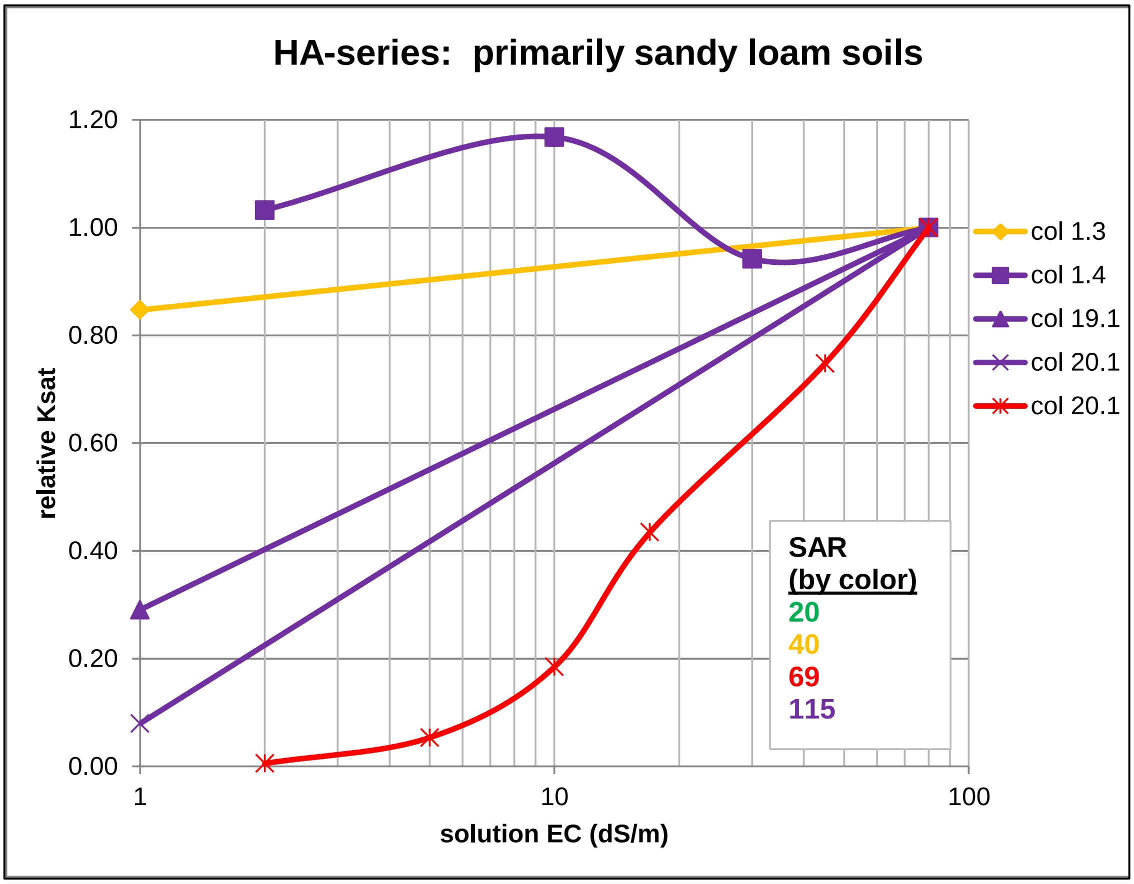
One example of such a synthesis is shown in Figure 5.23, whereby fine soil textures generally in the ‘clay loam’ category are synthesized for a field of sites near Lloydminster, Alberta. This is denoted as the “HA” series, and consists of approximately 15 experiments using cores with a predominantly clay loam texture. A range of different responses are observed for solution SAR values ranging from 20 to 115. Some samples display a typical reduction in hydraulic conductivity as EC is reduced, whereas other samples display minimal hydraulic conductivity loss over wide EC/SAR ranges. The latter samples tend to have low initial hydraulic conductivity and, as described in the previous sections, tend to be less sensitive to SAR-induced K_{sat} losses. It may be useful to consider this class of soils in a different manner to further refine the ability to predict K_{sat} losses based on initial hydraulic conductivity as well as EC/SAR combinations. It is also notable that the two samples tested with SAR=115 do not exhibit behavior visibly more sensitive than when tested with a lower SAR=69 value.

Figure 5.23. HA-series synthesis: fine (clay loam) soils



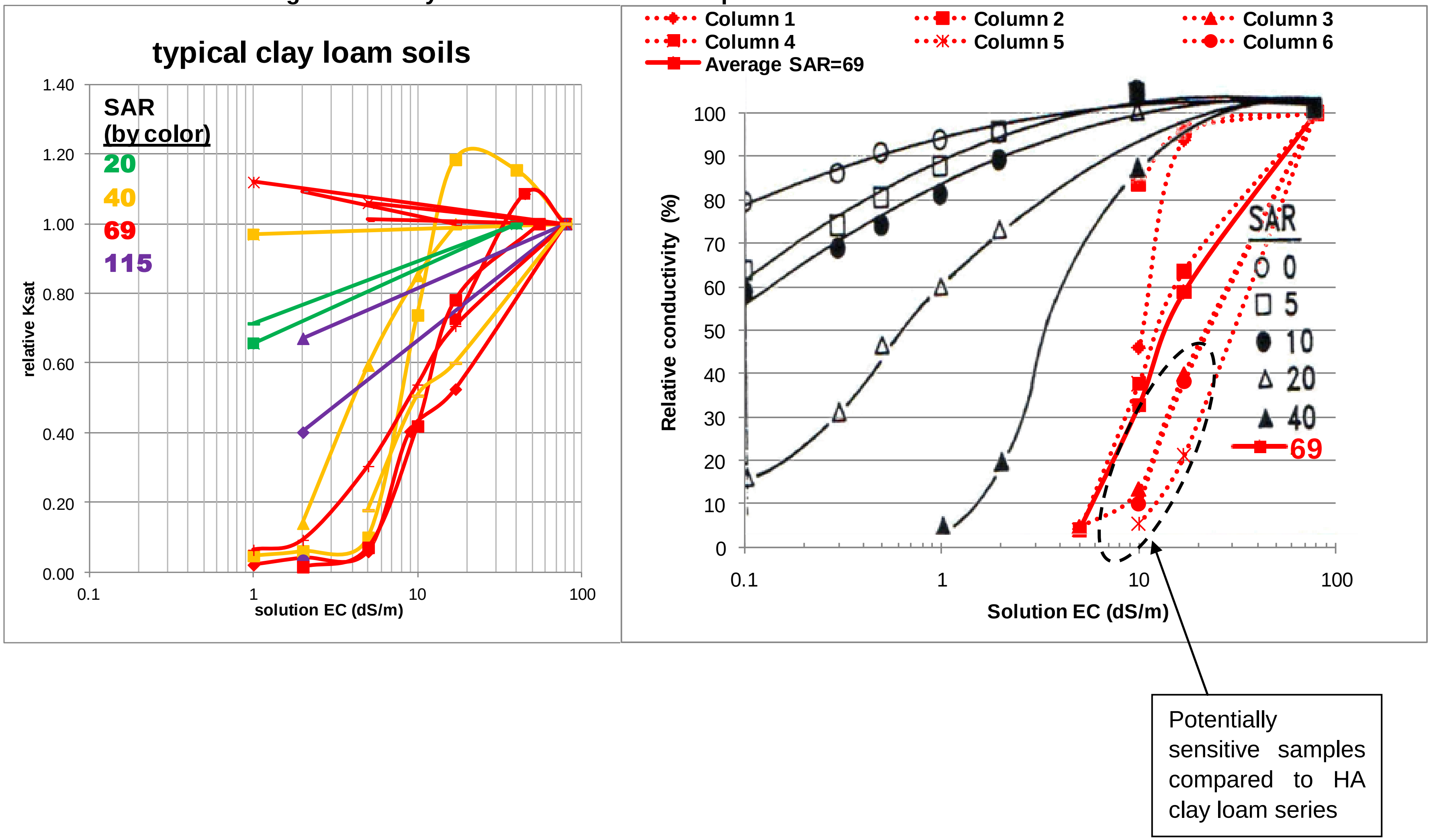
For comparison, Figure 5.24 shows a synthesis of the coarse (primarily sandy loam) soils from the HA-series. Since the sites in this series were primarily fine, a smaller number of coarse cores were evaluated compared to fine soils. The trends observed appear largely consistent with those observed using coarser soils from other sites, with examples such as col 1.3 and col 1.4 showing relatively insensitive soils to SAR values of 40 and 115 respectively. Some response is shown for two experiments at low EC with SAR=115 (col 19.1 and 20.1), though the exact shape of the response is not known due to the single endpoints tested (straight lines are shown on the figure as the simplest interpolation). It is noteworthy that a further test at SAR=69 on column 20.1 (after an intermediate remedial step after the EC=1, SAR=115 treatment) shows a response more typical of fine soils than coarse soils, though it is unclear whether this was influenced by the initial impacting/remediation stages.

Figure 5.24. HA-series synthesis: coarse (sandy loam) soils



For context, Figure 5.25 shows the Curtin curves for "Willows" soil along with the SAR=69 curves from Phase 1 (right) compared to the clay loam results from the HA series (left). It appears that some of the soils used in the SAR=69 experiments from Phase 1 may be more sensitive than the clay loam HA soils based on the presence of outlined potentially sensitive samples from Phase 1 which do not show corresponding behavior within the HA series. Some of these apparently sensitive samples from Phase 1 are from relatively dry cores from near Medicine Hat in southeast Alberta. These columns may potentially be influenced by other features of the initially dry cores (as-collected) and corresponding potential for low bulk-density, channels, or macro-pores from cores from this dry area with deep water tables.

Figure 5.25. Synthesis of HA-series compared to literature and Phase 1 results



As a further synthesis of leaching column results between sites and soil series, Figure 5.26 shows all results for columns tested using the same methodology of fixing SAR values while reducing EC and measuring relative K_{sat}. A range of sites/regions are shown, including series denoted as 'IP', 'L', 'JA', 'QA', 'HA', and 'TR' as discussed earlier (and with full leaching responses shown in the Appendix). It is notable that one series in particular ('QA') had several samples show increasing hydraulic conductivity with decreasing EC at fixed SAR. These tended to be coarser samples, and may be related to the high volumes of fluid leached and potential reorientation of clay particles/layers from the originally presumed horizontal orientation to an induced vertical orientation due to the rapid vertical flow through the columns. Figure 5.27 shows the same figure but with the QA series removed to allow for more resolution on the vertical scale.

Figure 5.26. Synthesis of all variable EC / fixed SAR experiments

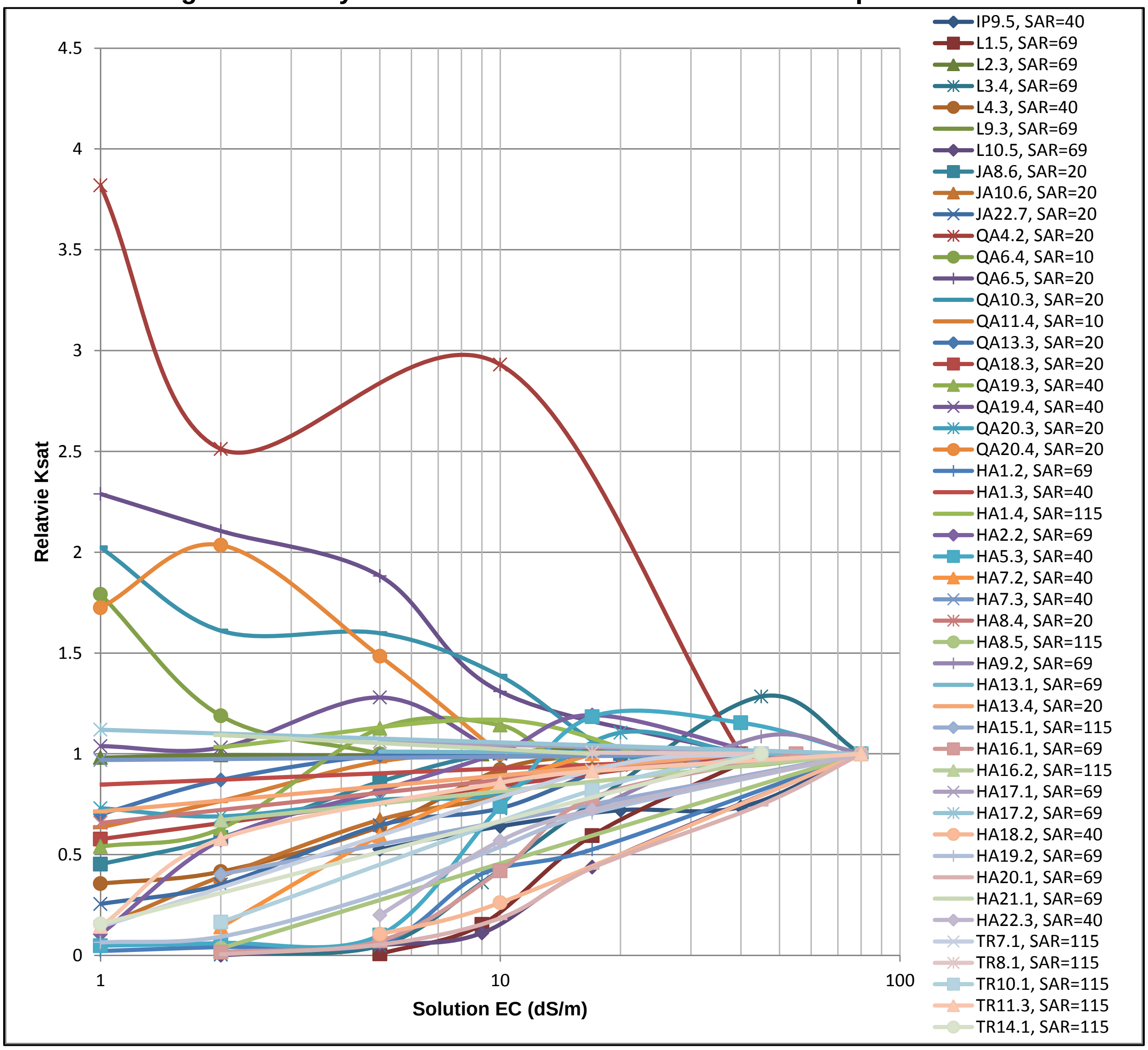
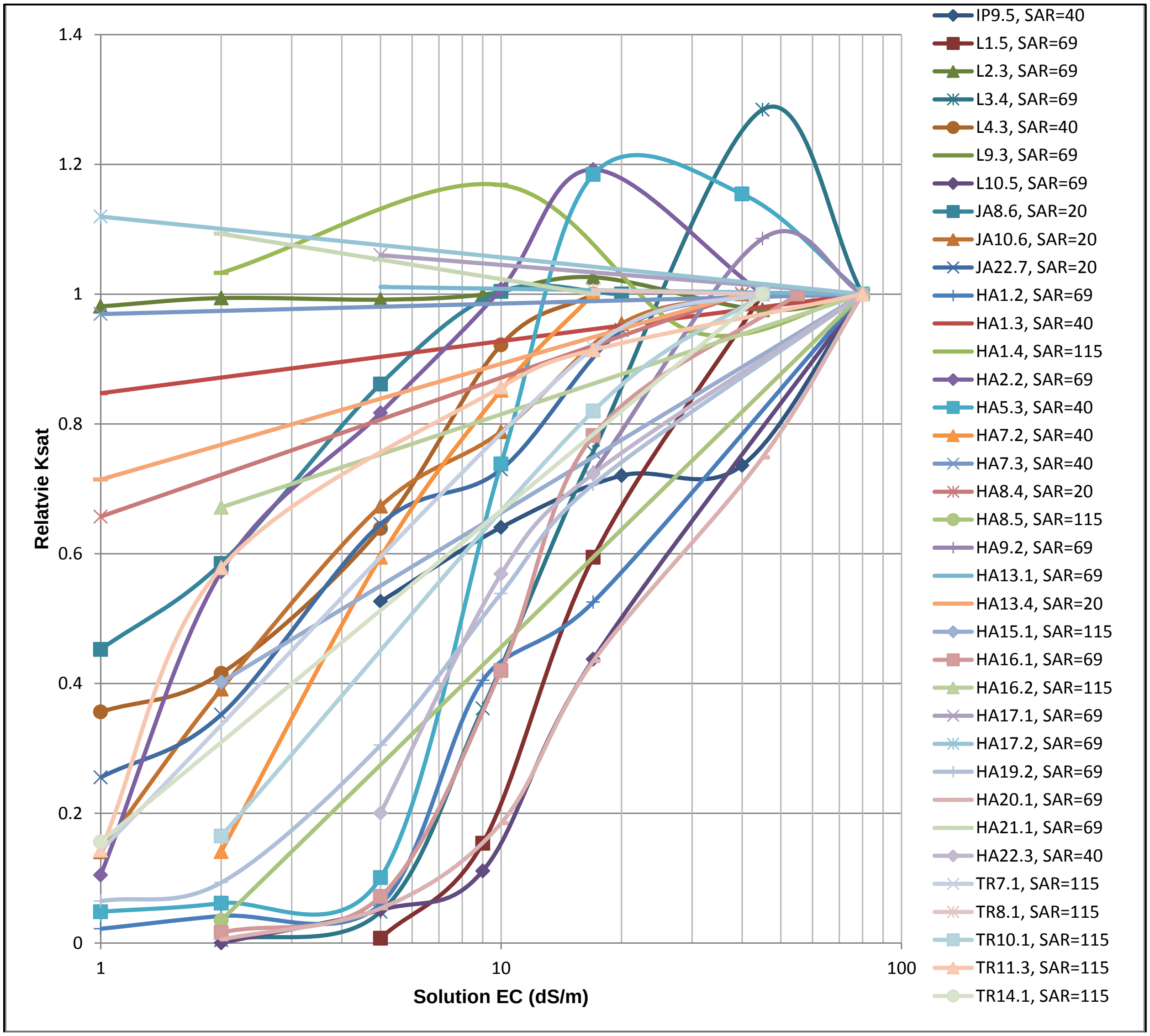


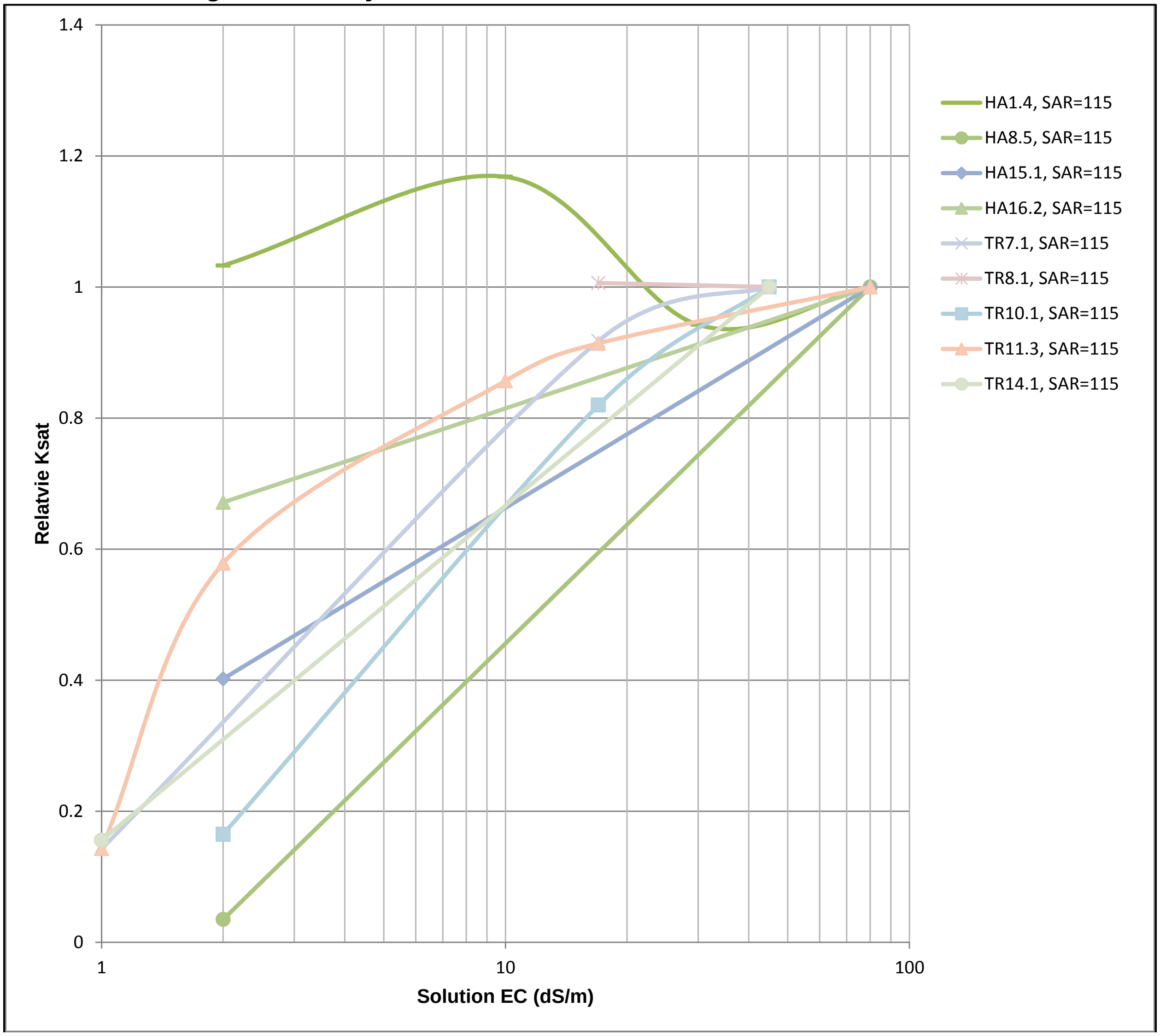
Figure 5.27. Synthesis of all variable EC / fixed SAR experiments (QA series removed)



Note: QA series excluded due to relative lack of effect

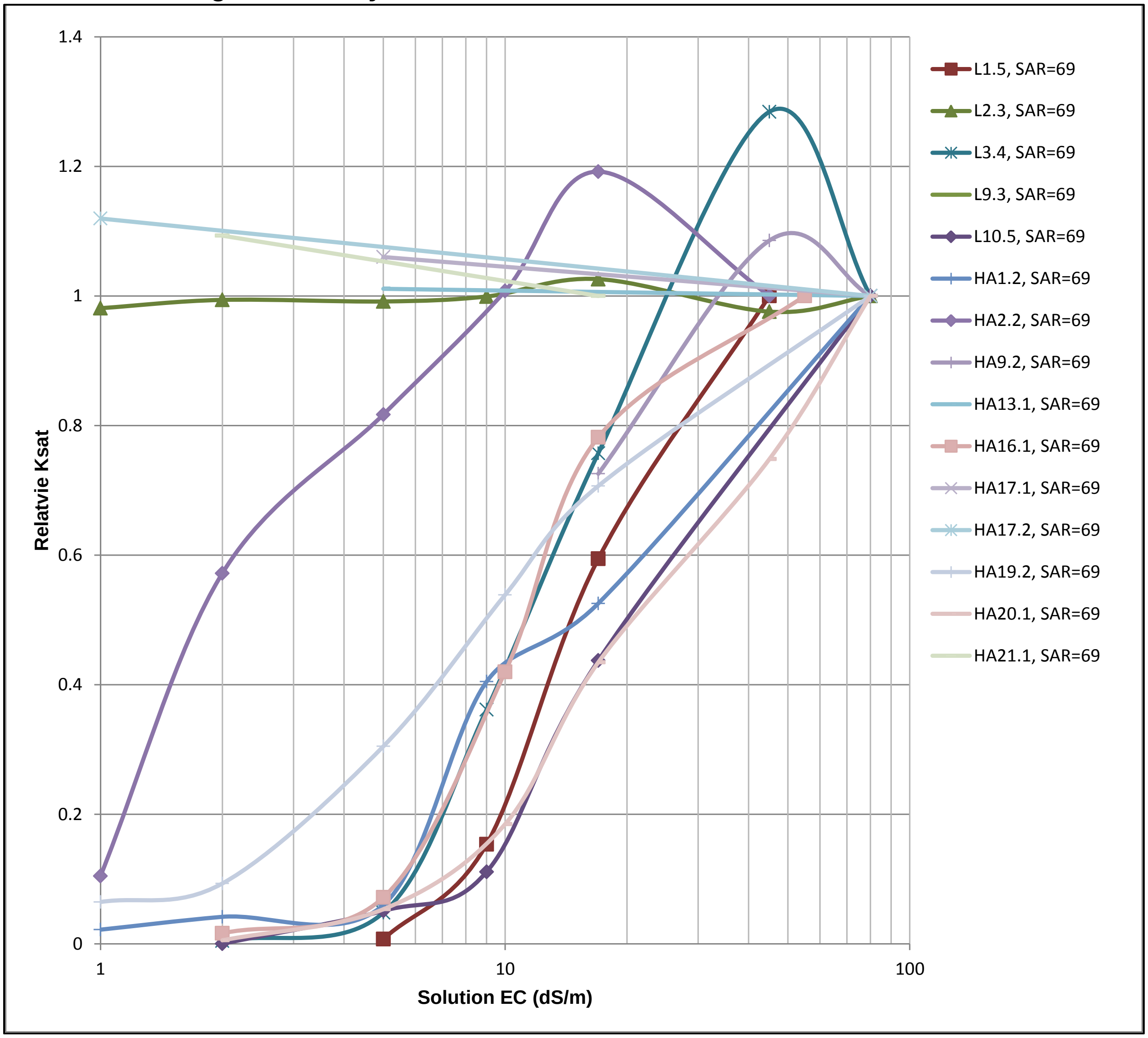
Since the figure above shows all SAR series simultaneously, it is useful to consider each SAR series separately to allow comparisons and evaluate relative influences on K_{sat}. Figures 5.28 through Figure 5.31 show the above data (QA series removed) for SAR=115, 69, 40, and 20 respectively. Though differences in texture have not been considered in these figures, it is noteworthy that the responses to SAR=115 do not visibly appear significantly different than the responses to SAR=69. This potentially suggests some possible effect plateau at high SAR levels, though it is important to note that testing at SAR=115 was most often performed on low-sensitivity samples in order to maximize the likelihood of observing a response. This SAR=115 dataset thus does not contain as many sensitive samples as were tested at SAR=69 or SAR=40. The figure with SAR=40 generally appears less sensitive than SAR=69, and the SAR=20 figure shows less sensitivity than SAR=40.

Figure 5.28. Synthesis of all variable EC series with SAR=115



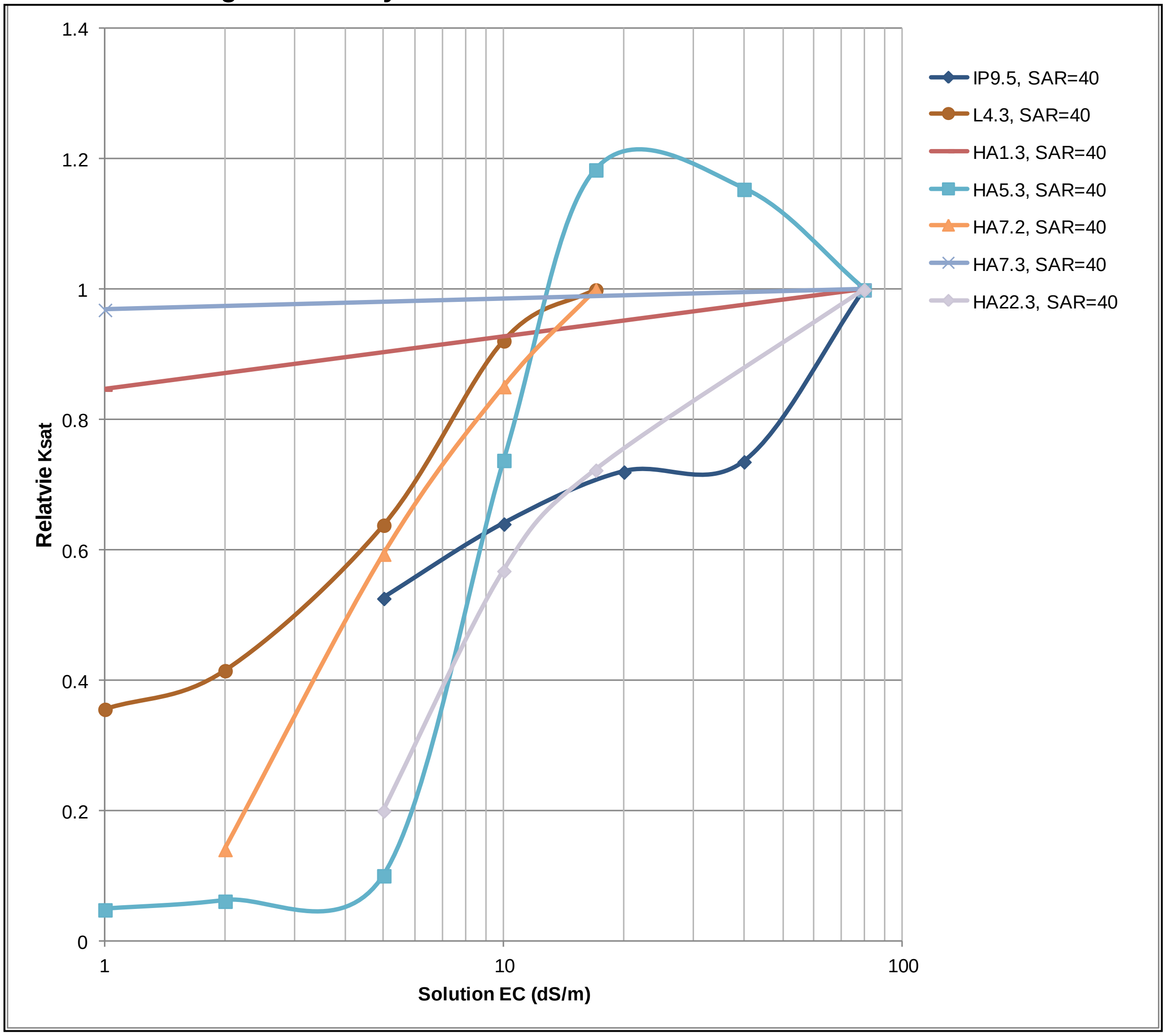
Note: QA series excluded due to relative lack of effect

Figure 5.29. Synthesis of all variable EC series with SAR=69



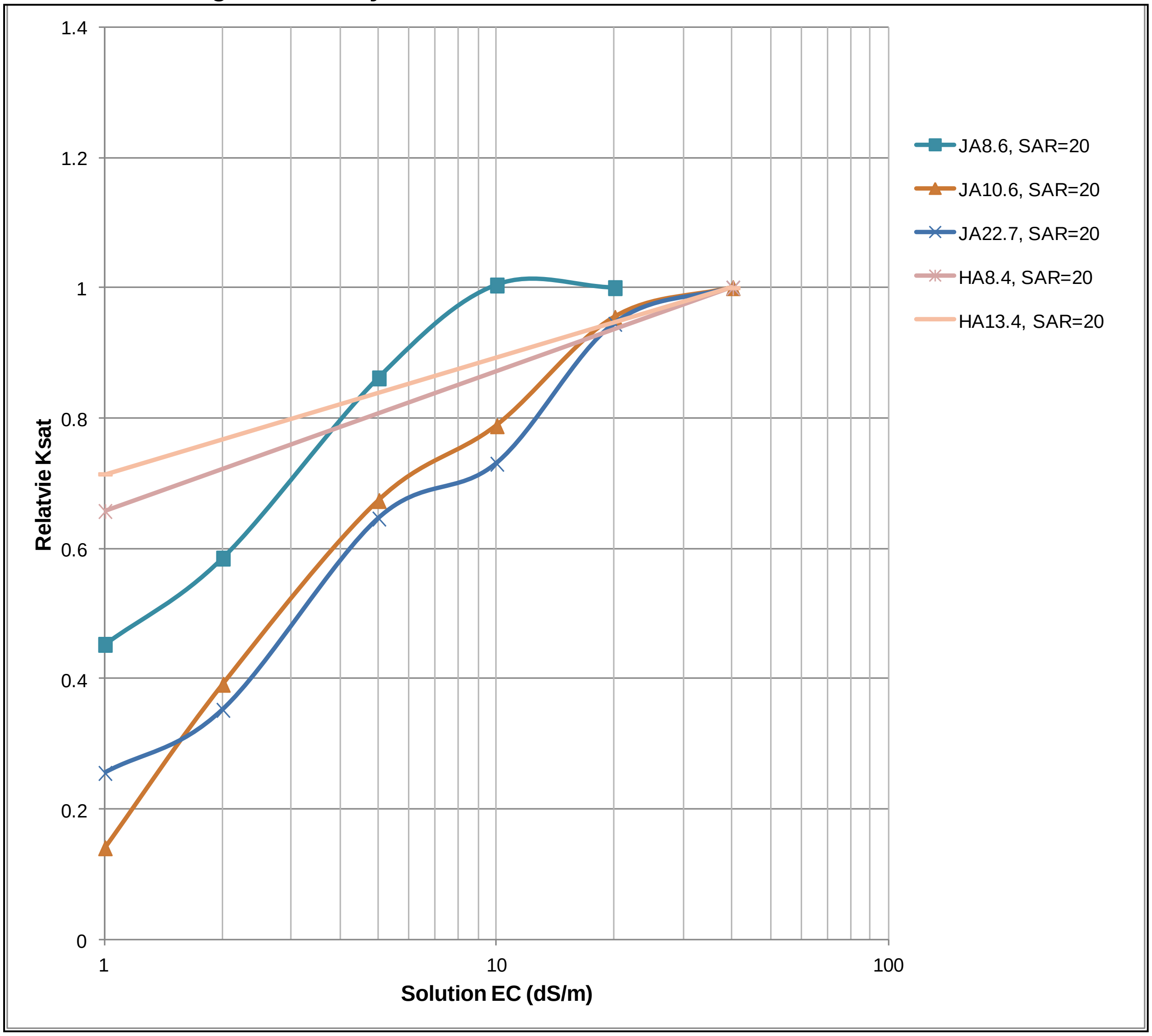
Note: QA series excluded due to relative lack of effect

Figure 5.30. Synthesis of all variable EC series with SAR=40



Note: QA series excluded due to relative lack of effect

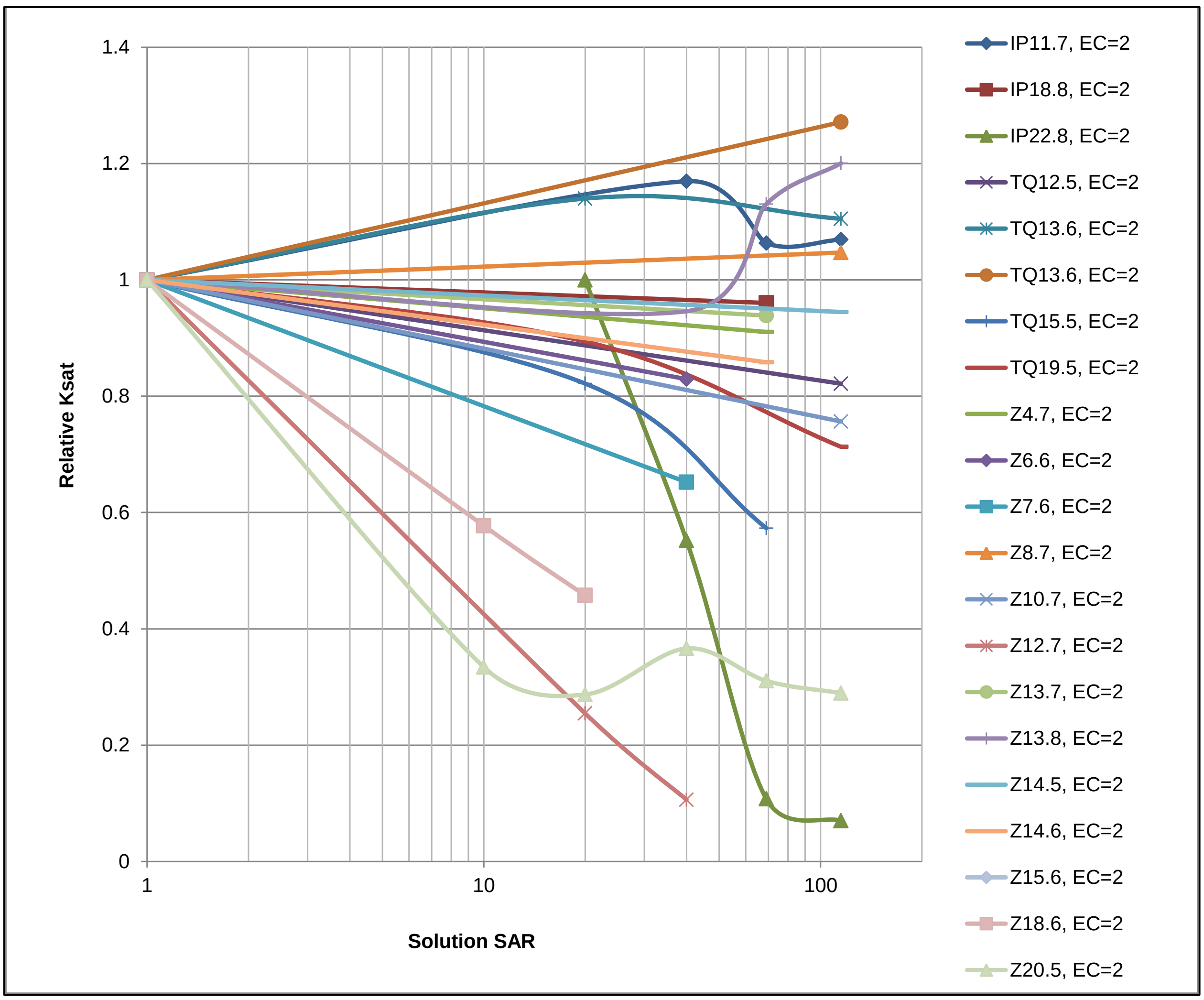
Figure 5.31. Synthesis of all variable EC series with SAR=20



Note: QA series excluded due to relative lack of effect

An alternative testing technique used in some columns was to keep a fixed EC value while increasing SAR from low values to high (as opposed to fixing SAR while varying EC as previously described and used in literature). Examples of this are shown in Figure 5.32, showing a variety of soil series ('IP', 'TQ', and 'Z') tested at a fixed EC of 2 while SAR is increased from 1 up to higher values (often up to 69 to 115). In many cases minimal effects were noted, primarily for soils with very low initial hydraulic conductivity due to highly-compacted clays or clay loams. Some experiments did show more visible responses, however, with some samples showing more than a 2-fold K_{sat} reduction (K_{rel} less than 0.5) for SAR values generally above 20 for this fixed (and relatively low) EC of 2.

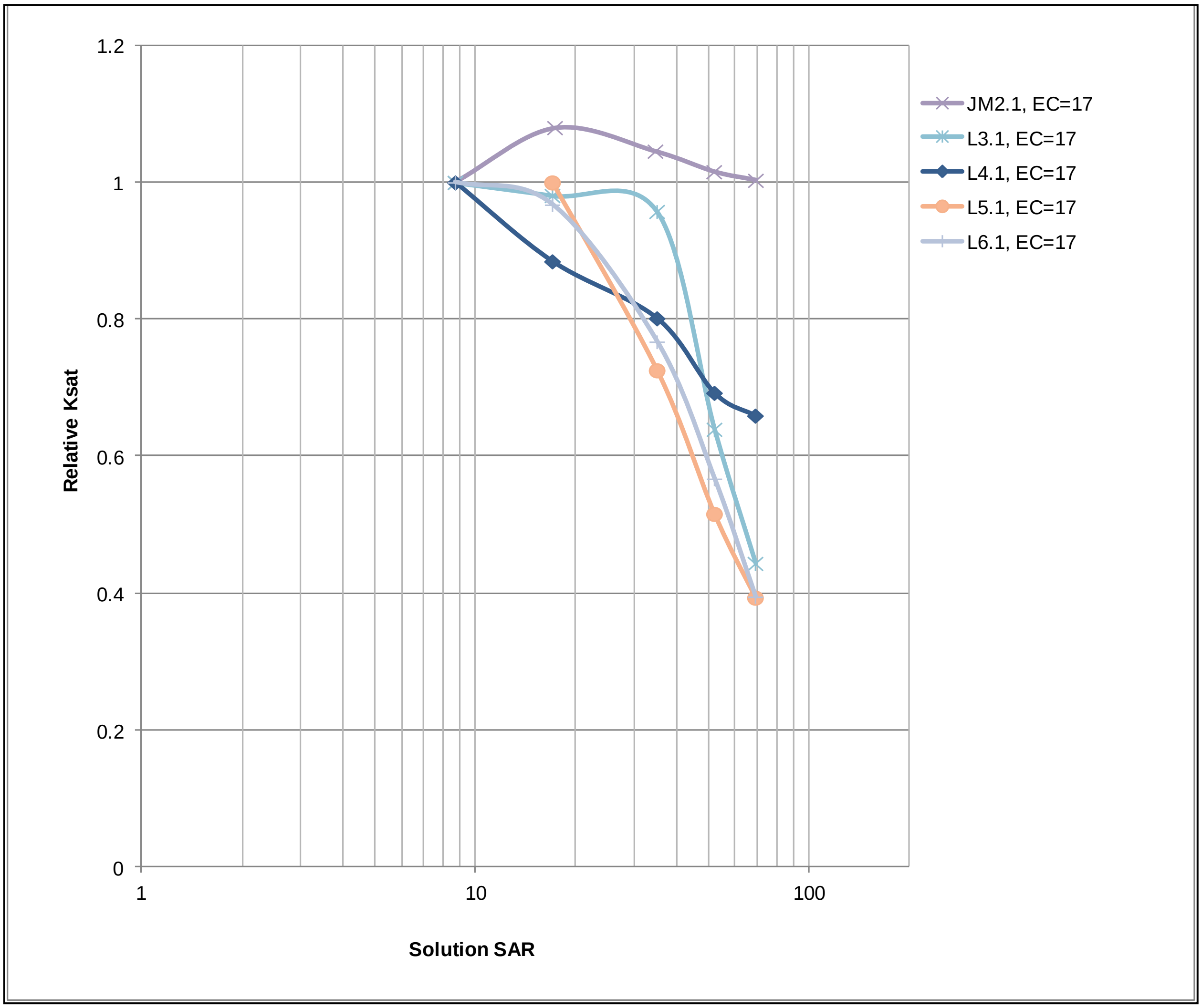
Figure 5.32. Synthesis of variable SAR series with fixed EC=2



Note: QA series excluded due to relative lack of effect

Figure 5.33 shows an analogous figure but with a fixed EC of 17 rather than 2. These experiments were generally performed with soils from the L-series from near Medicine Hat, with the three L-series experiments showing visible K_{sat} reductions at SAR values above 10 at this fixed EC value of 17. As discussed previously during Phase 1 experiments, these L-series cores appear to be potentially more sensitive than many of the others tested during this research. This may be partially due to the cores being initially fairly dry due to the deep water table, with the potential for macro-pores or low bulk density potentially resulting in behavior somewhat different from samples obtained below the water table.

Figure 5.33. Synthesis of variable SAR series with fixed EC=17



Note: QA series excluded due to relative lack of effect

Soils with different textures likely differ in their response to EC/SAR combinations as shown in the repacked literature soils described in Section 2.2. As a preliminary examination of this effect, soils were grouped as either high- or low- clay content (≥27% and <27% clay, respectively) and their SAR response curves plotted and compared. This initial 27% clay content classification is based on the approximate transition between 'loam' and 'clay loam' textures, though other classification systems (potentially with more categories) may show additional insight beyond those described below.

Figures 5.34 to 5.37 examine the differing sensitivities of K_{sat} changes based on these two broadly defined soil texture categories in response to variable EC solutions with fixed SAR. The QA series was included in this analysis since its relative lack of SAR response is likely related to the relatively coarse texture and is thus useful to consider in this textural analysis. Figures 5.38 and 5.39 show analogous curves with variable SAR and fixed EC.

In general, there appears to be some trend toward increased sensitivity with higher clay content, though there remains visible variability within each of these two broad soil categories. For example, the SAR=40 comparison shows a visible effect for several high-clay cores and relatively minor effects with the lower-clay cores. Similarly, the SAR=20 series also shows a large number of cores (primarily the QA series of loam / sandy loam soils) which are insensitive to SAR and show an increase in hydraulic conductivity presumably due to other potential factors such as layer or platelet reorientation during leaching as previously discussed.

The range of behavior demonstrated by these graphs also suggests that factors other than clay content likely play a role in SAR/EC effects on hydraulic conductivity. For example, several samples in the SAR=69 series (primarily the HA-series of clay loam soils) show relatively minor response to SAR despite having a relatively high clay content. Similarly, several high-clay samples also show minimal effects at high SAR values (>40) in the fixed EC=2 graphs, including the TQ-series and Z-series of clay loam and clay soils. These low-sensitivity, clayey soils generally all have a low initial hydraulic conductivity ($<1x10^{-9}$ m/s), consistent with their relatively high dry bulk density (typically 1.7 – 2.0 kg/L). This suggests that lightly-compacted (or potentially fractured / channeled) clayey soils may be more sensitive to K_{sat} losses than dense, highly compacted clayey soils. It also appears likely that sandier soils may also be influenced by similar non-clay factors such as bulk density and/or initial hydraulic conductivity.

Figure 5.34. Comparison based on soil texture of responses to variable EC with fixed SAR=115

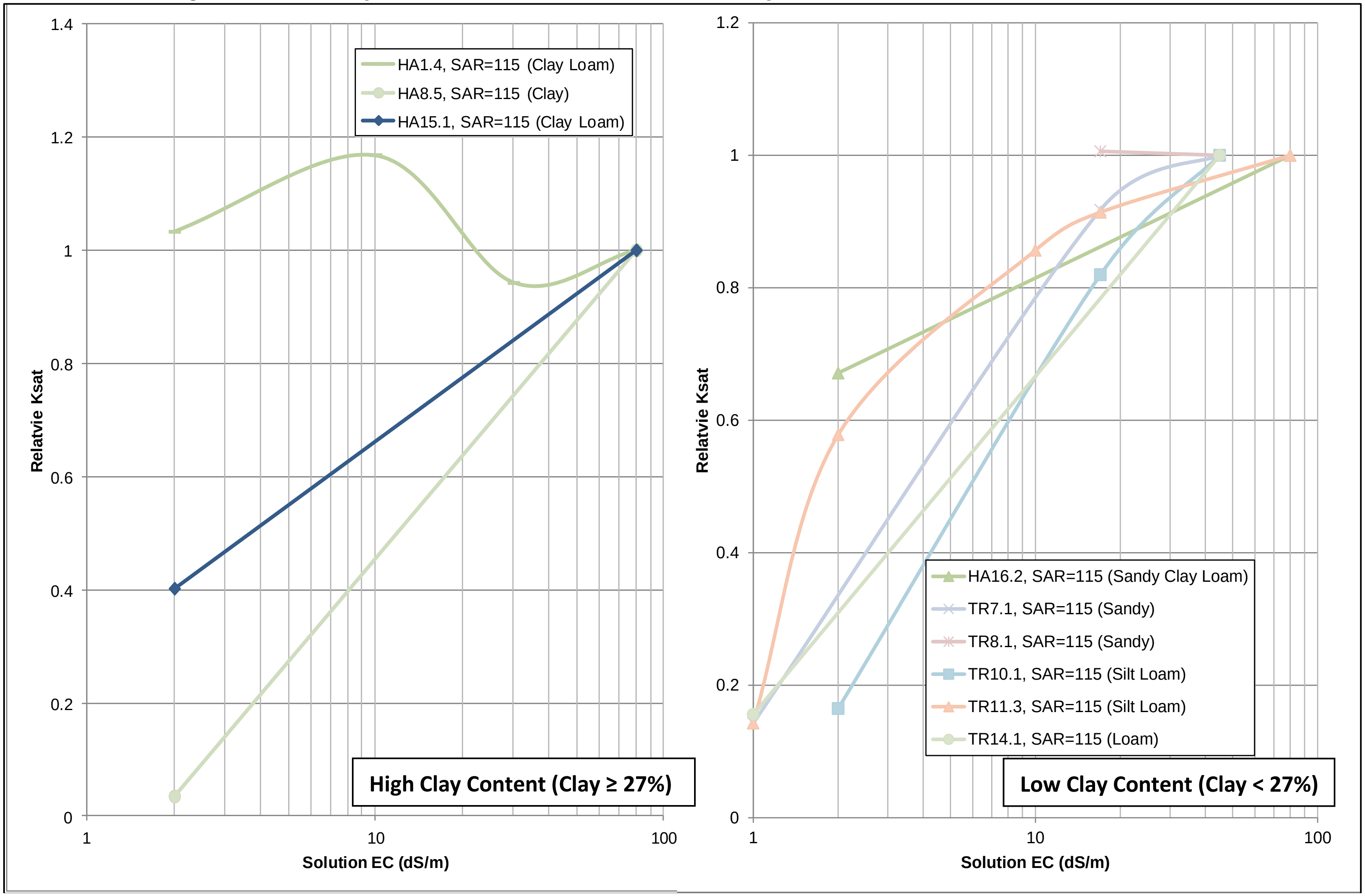
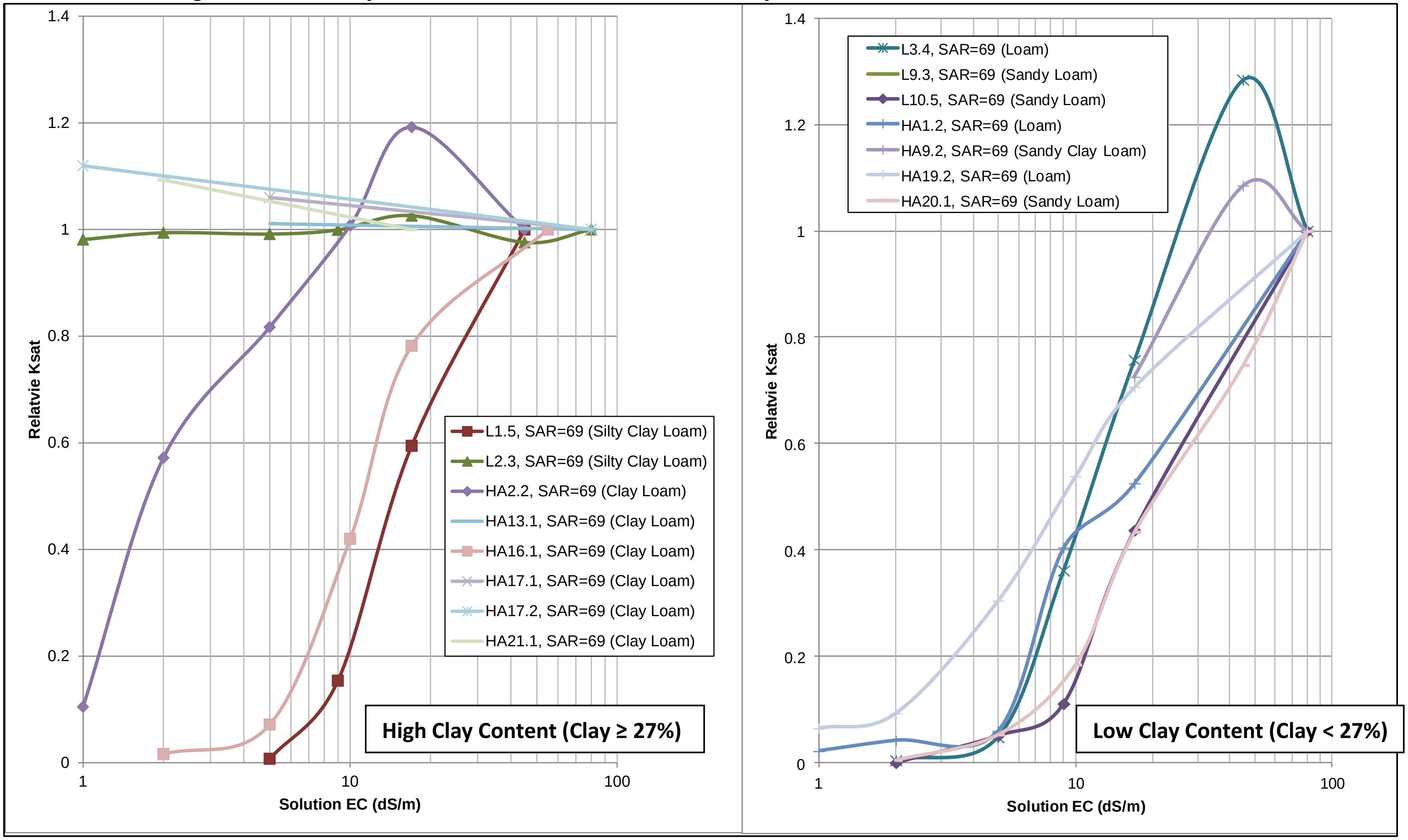
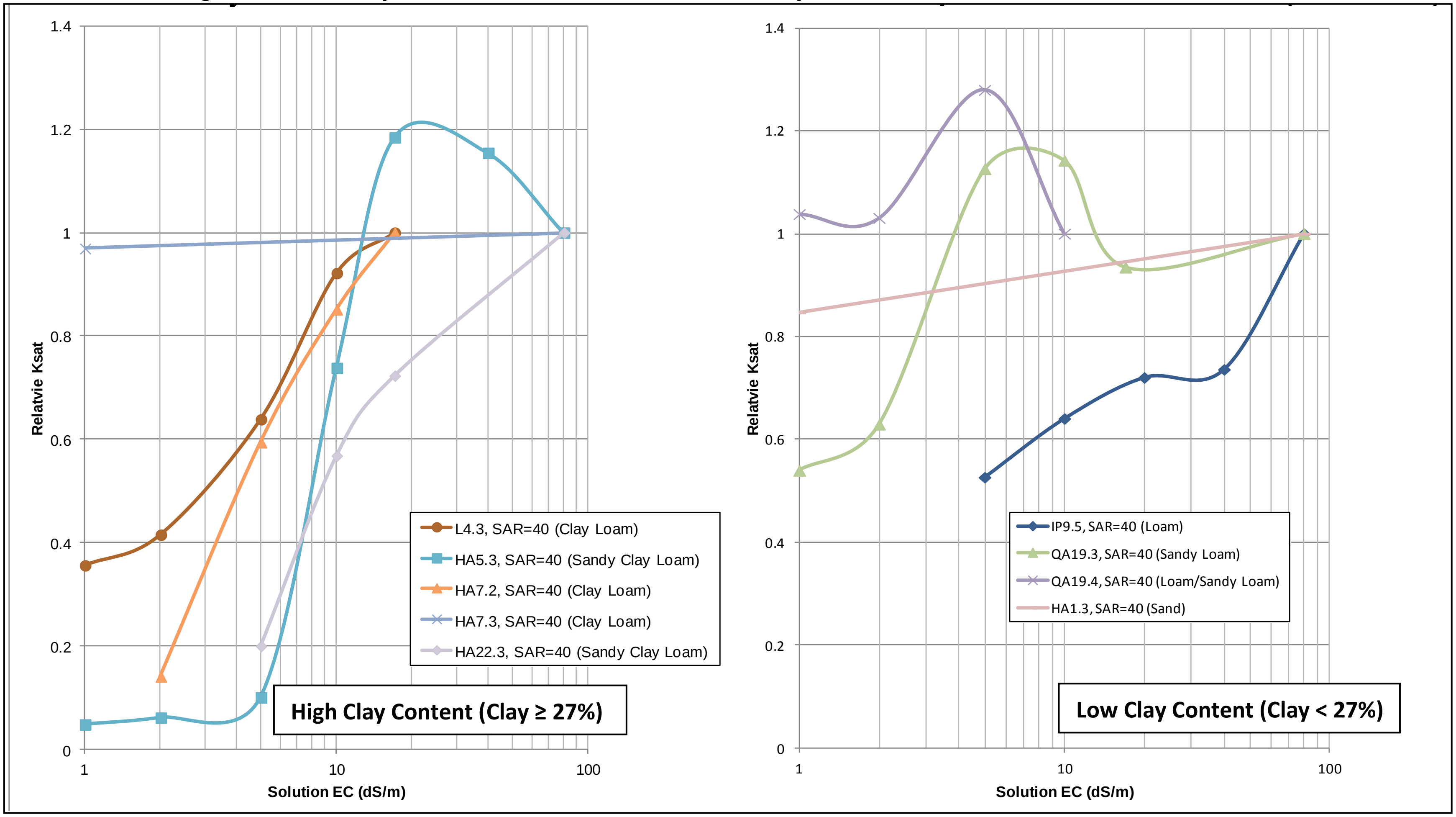


Figure 5.35. Comparison based on soil texture of responses to variable EC with fixed SAR=69



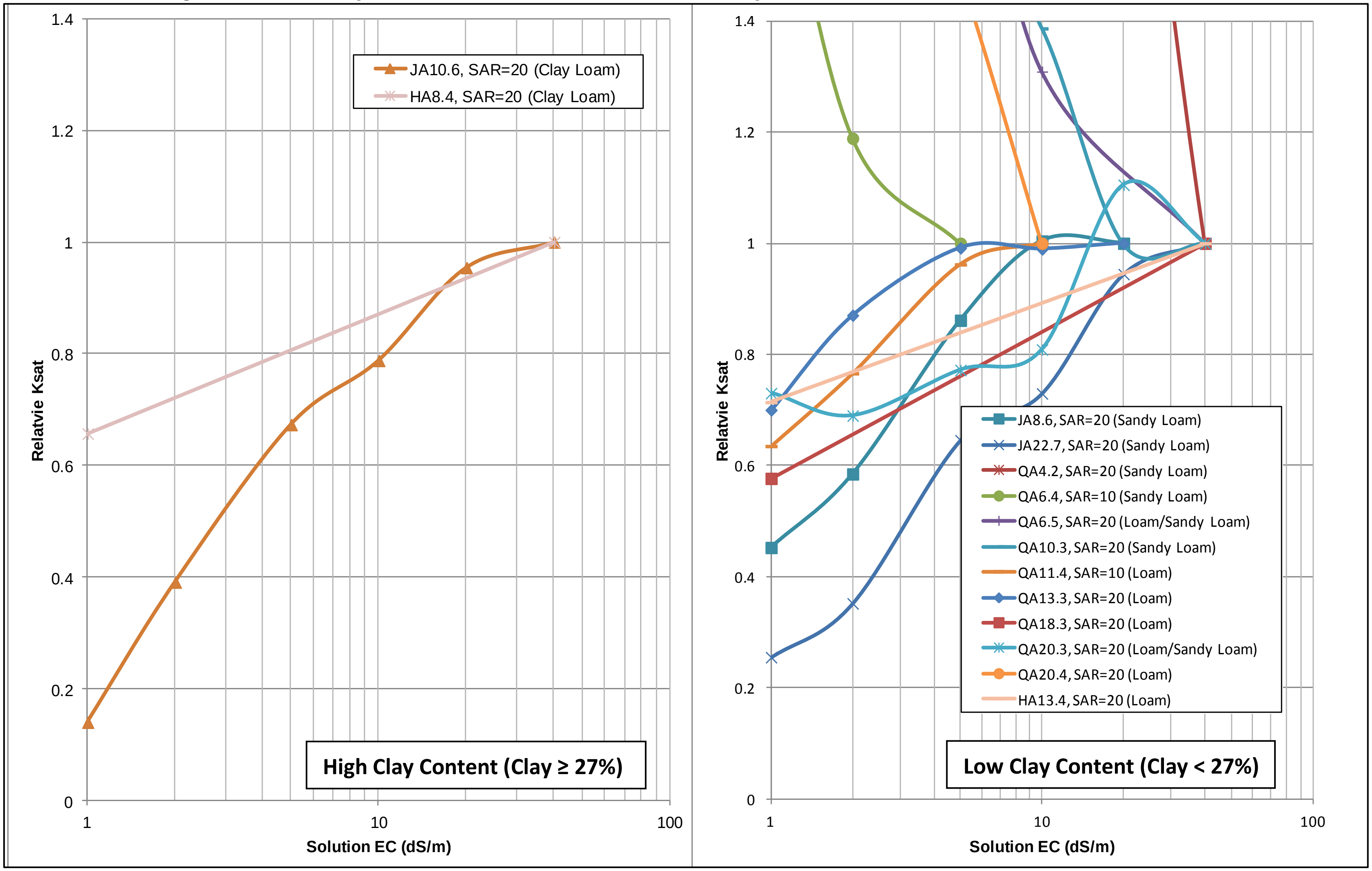
Note: QA series included

Figure 5.36. Comparison based on soil texture of responses to variable EC with fixed SAR=40



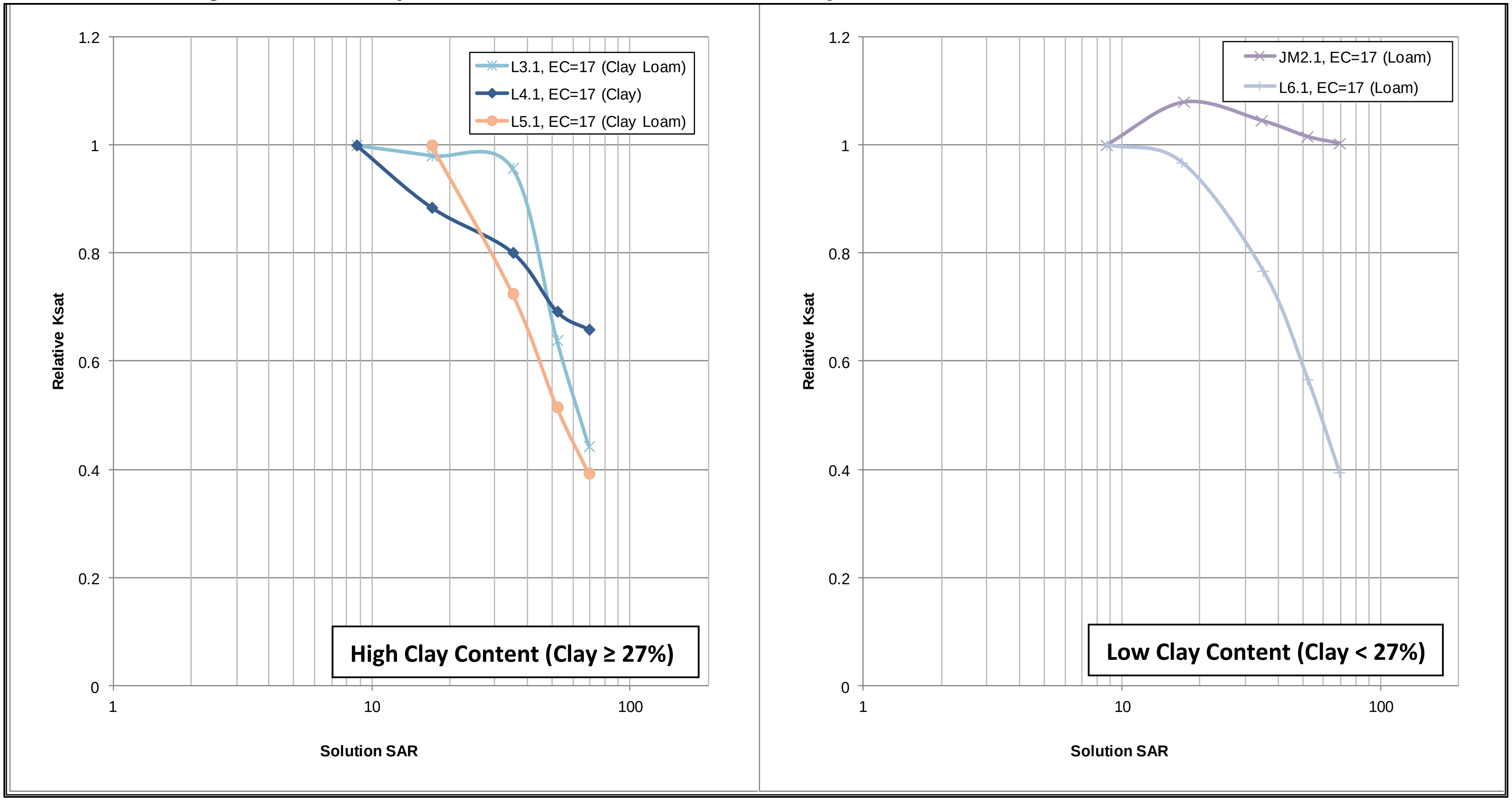
Note: QA series included

Figure 5.37. Comparison based on soil texture of responses to variable EC with fixed SAR=20



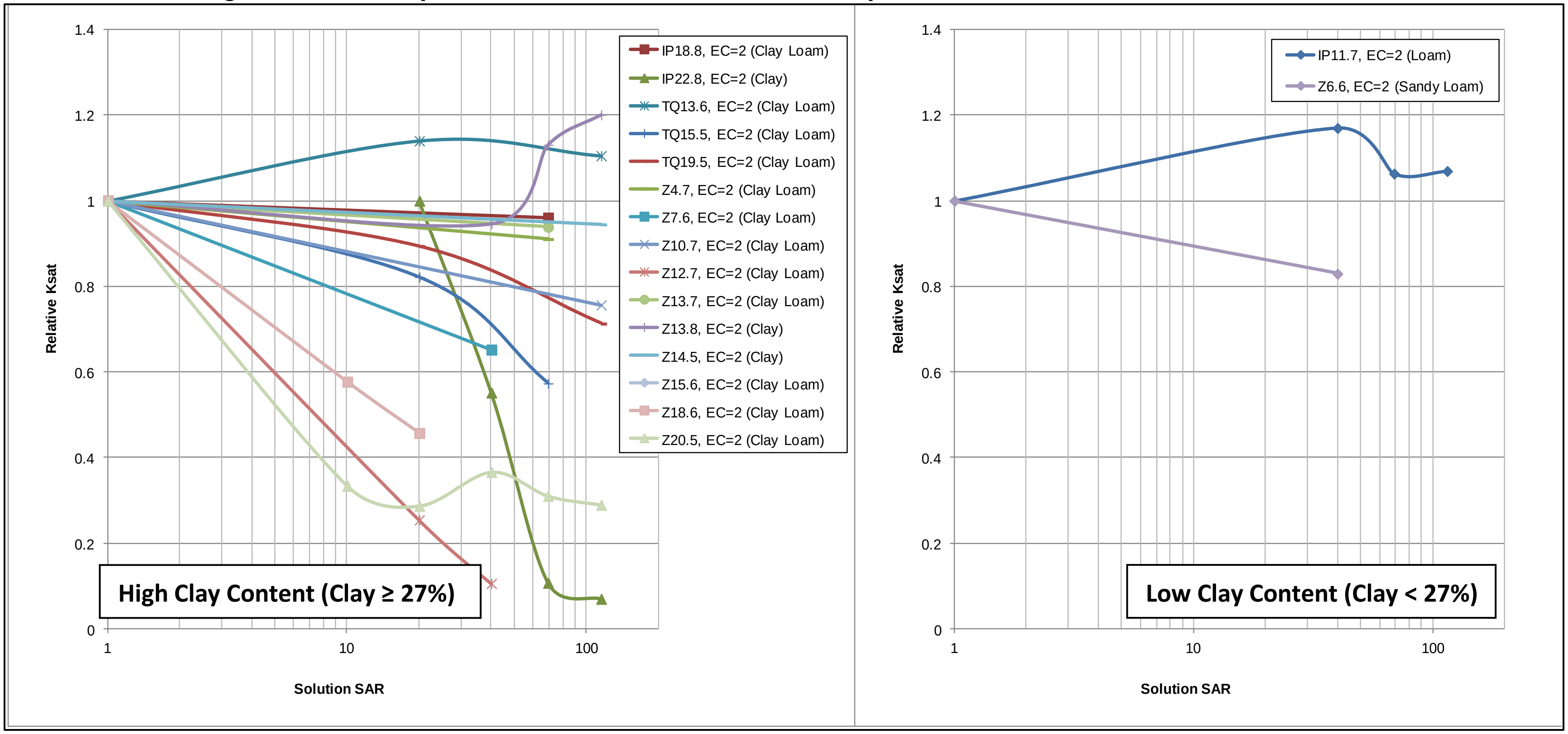
Note: QA series included

Figure 5.38. Comparison based on soil texture of responses to variable SAR with fixed EC=17



Note: QA series included

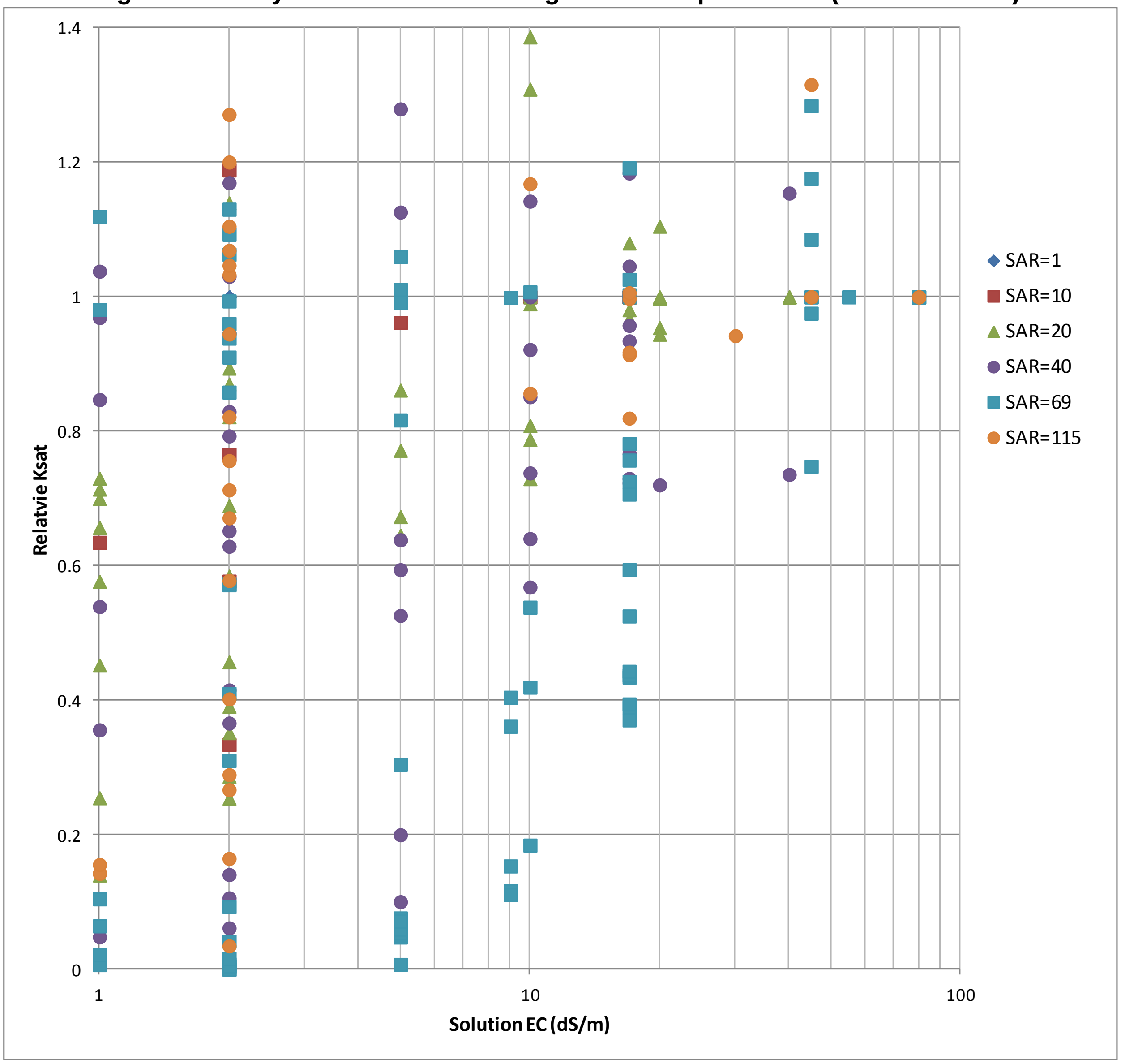
Figure 5.39. Comparison based on soil texture of responses to variable SAR with fixed EC=2



Note: QA series included

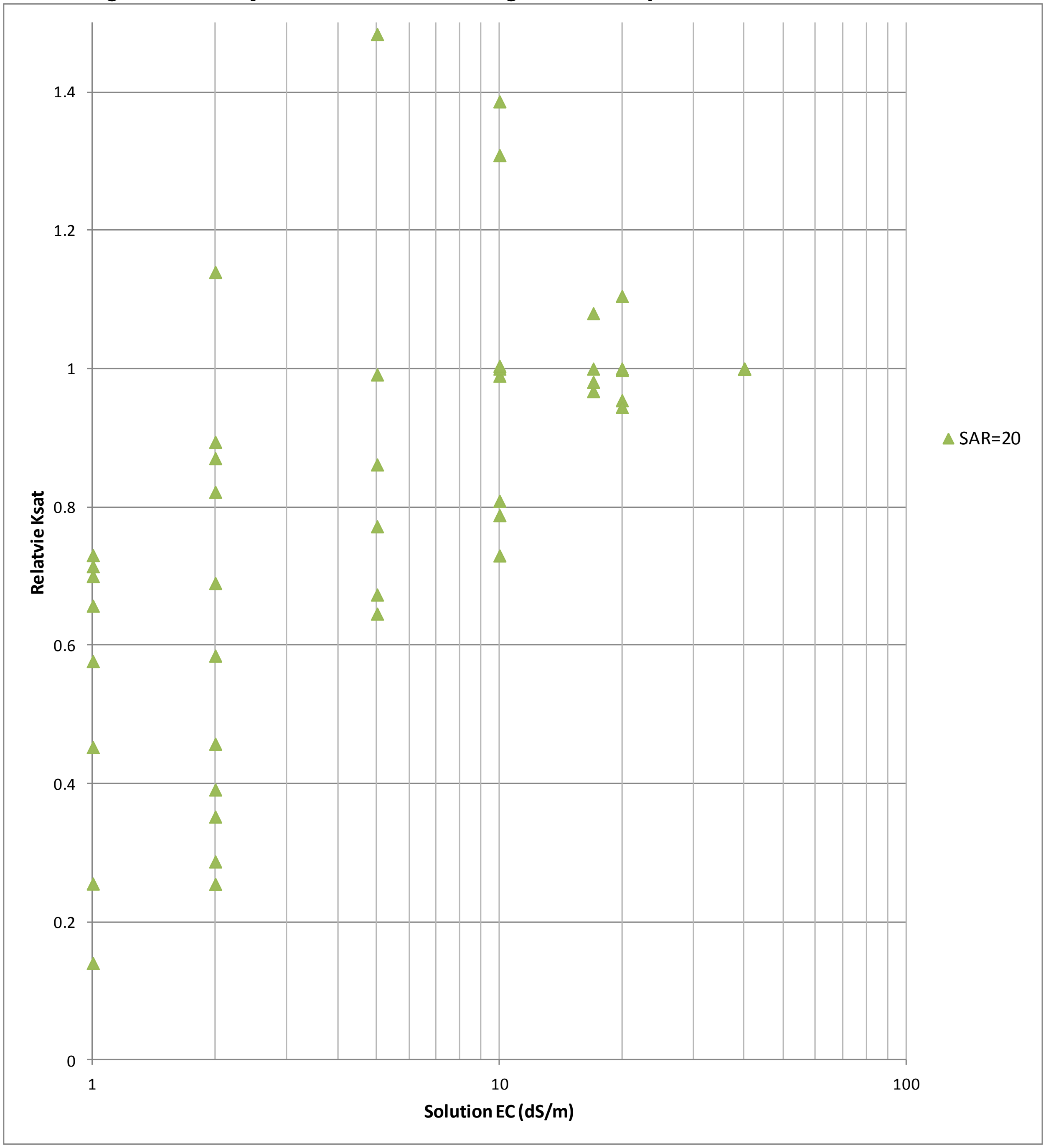
One method of combining the leaching column results from both testing methods (either fixed EC or fixed SAR) is to plot individual EC/SAR/K_{sat} combinations as distinct data points without considering the exact path the experiment followed from baseline to impacted. Figure 5.40 shows an example of such an overall synthesis, showing datapoints color-coded by SAR and plotted on a K_{sat} vs EC figure. In general, the largest K_{sat} reductions at EC values above 5 dS/m tended to be for SAR values of 69 and 115, as expected. There was a wide range in observed response, however, with SAR values of 69 and 115 also showing several soils which were relatively insensitive to SAR effects (K_{sat} remaining near 1 at low values of EC). SAR values of 40 tended to have reduced K_{sat} effects compared to a SAR of 69, with SAR values of 20 and 10 showing less response yet.

Figure 5.40. Synthesis of all leaching column experiments (both methods)



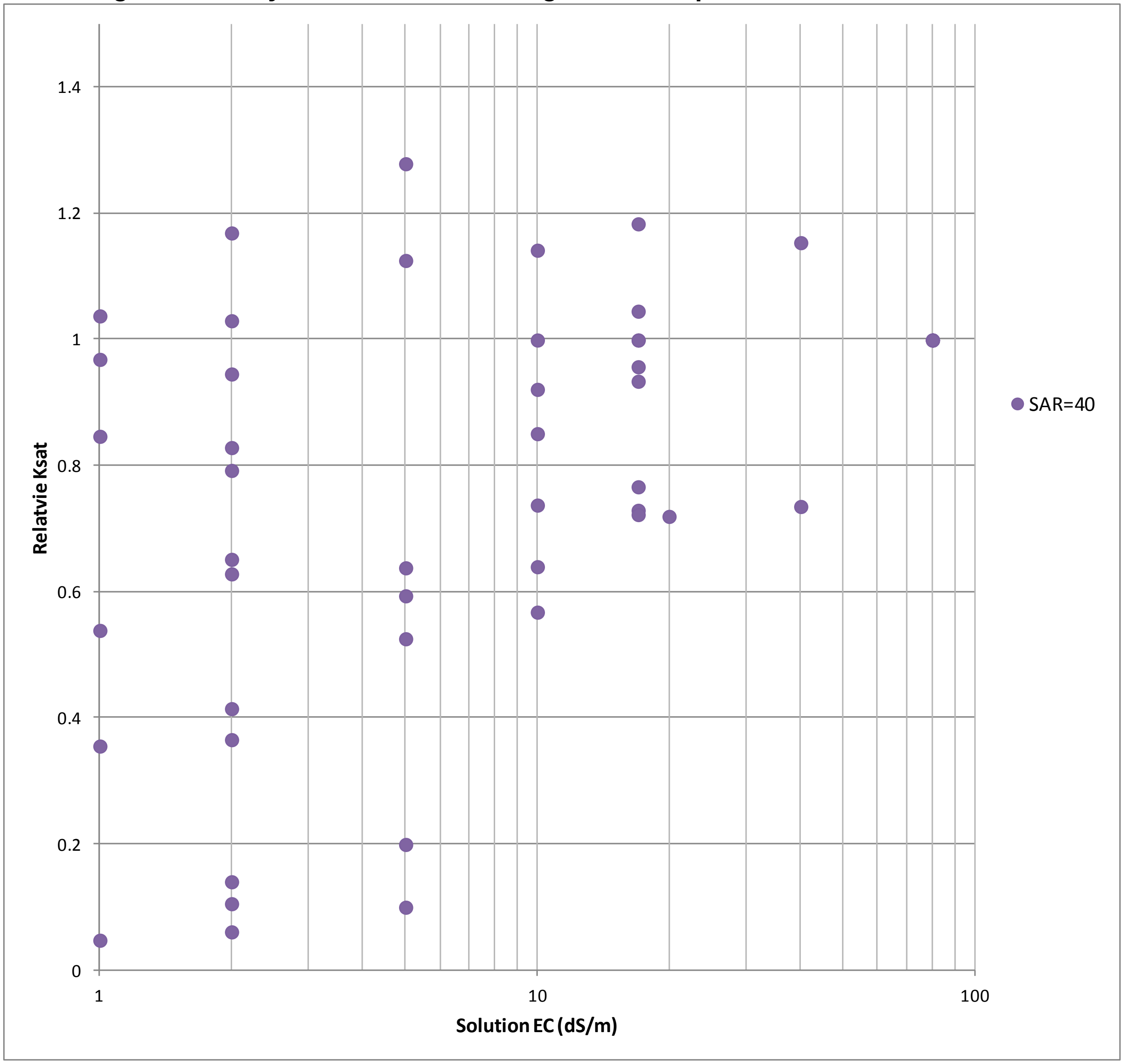
** Note: QA series excluded due to relative lack of effect*

Figure 5.41. Synthesis of all leaching column experiments at fixed SAR=20



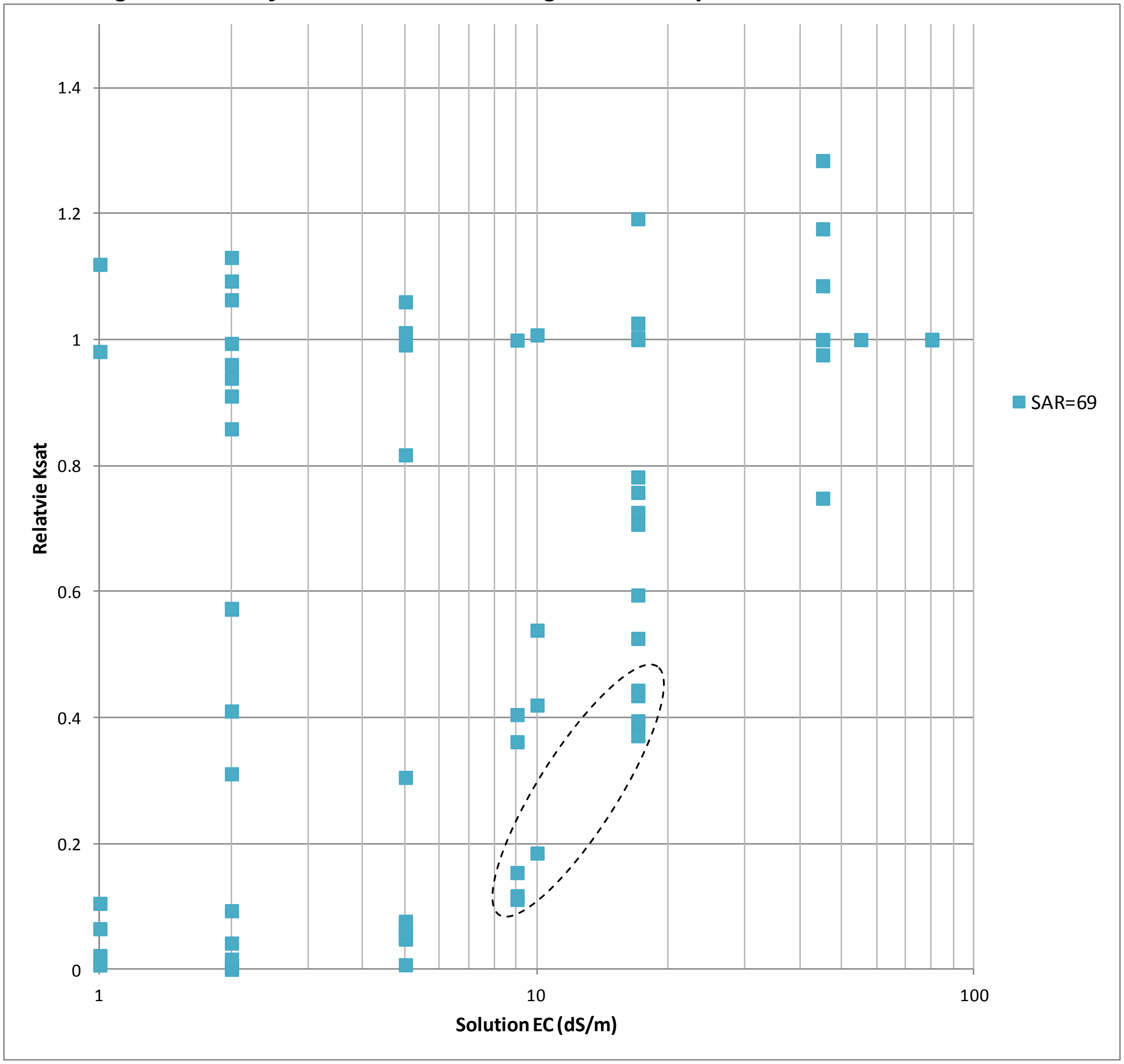
** Note: QA series excluded due to relative lack of effect*

Figure 5.42. Synthesis of all leaching column experiments at fixed SAR=40



** Note: QA series excluded due to relative lack of effect*

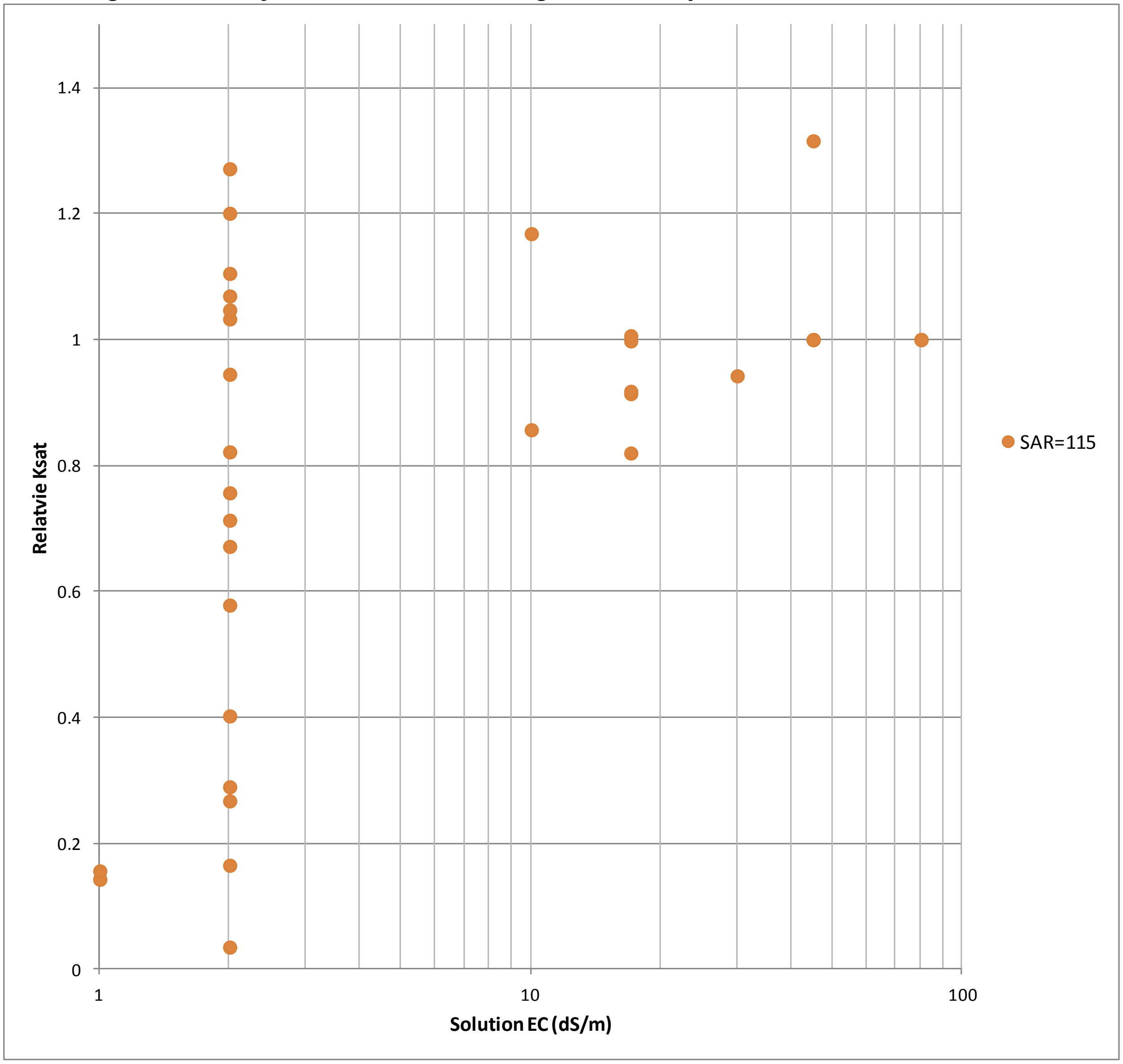
Figure 5.43. Synthesis of all leaching column experiments at fixed SAR=69



** Note: QA series excluded due to relative lack of effect.*

The outlined (most sensitive) samples are primarily from the L-series consisting of initially relatively dry soil cores from near Medicine Hat.

Figure 5.44. Synthesis of all leaching column experiments at fixed SAR=115



** Note: QA series excluded due to relative lack of effect*

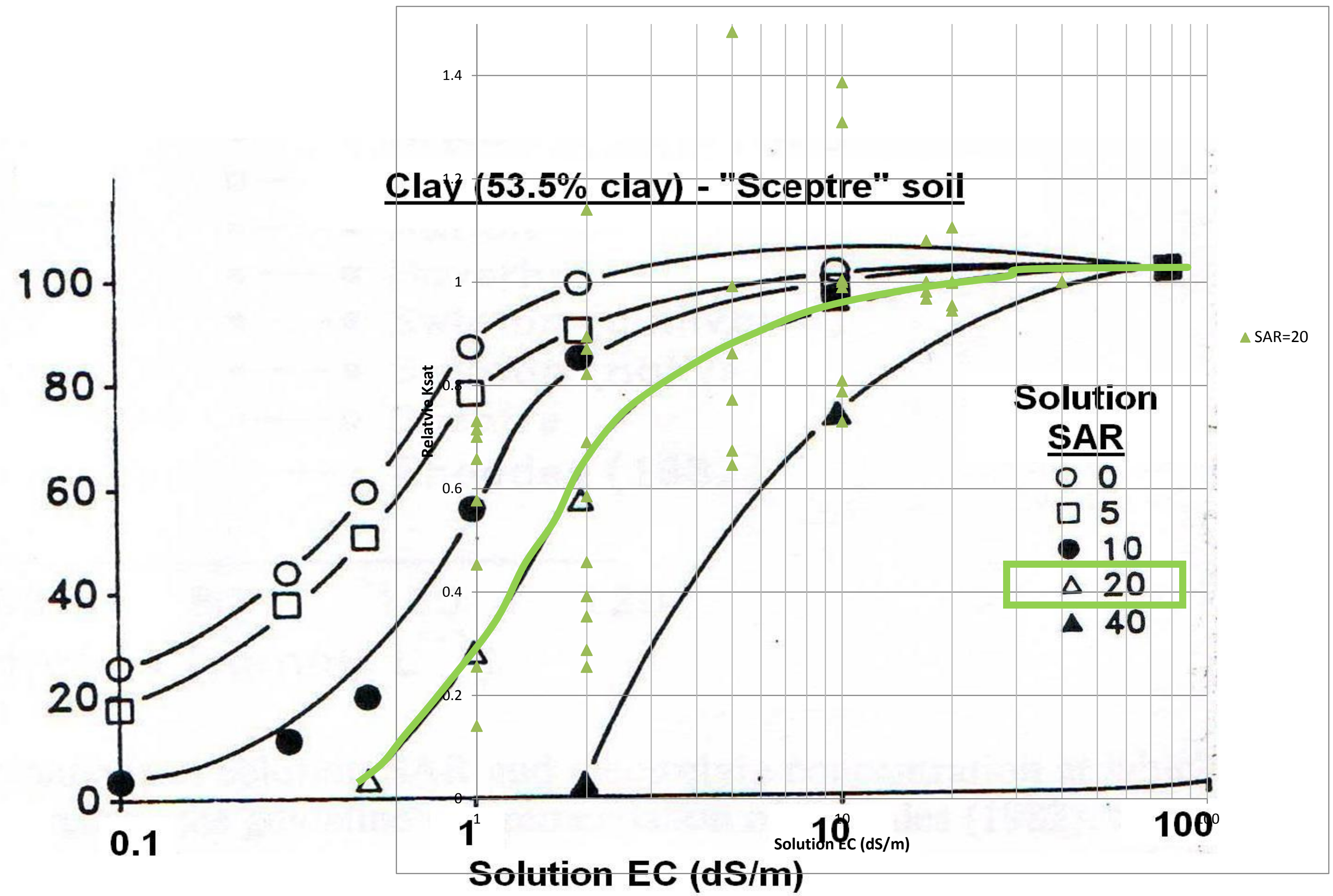
Note that testing at SAR=115 was most often performed on low-sensitivity samples in order to maximize the likelihood of observing a response. This SAR=115 dataset thus does not contain as many sensitive samples as were tested at SAR=69 or SAR=40.

It is notable that the most apparently sensitive samples from the above SAR=69 figure are from the L-series consisting of initially relatively dry soil cores from near Medicine Hat. These samples are outlined in black, and show relatively higher K_{sat} reductions at moderate EC's (approximately 9-17 dS/m on a solution basis) for a given SAR. As discussed earlier in this section, it is unclear whether this apparent sensitivity is due to soil texture or other factors such as the cores being from initially dry soils and thus potentially prone to macro-pores or channels which could potentially close during leaching with elevated SAR. These samples also tended to be lower dry bulk density (typically <1.4), which appears to increase the potential for relative K_{sat} losses.

Figures 5.45 through 5.47 show the SAR=20, SAR=45, and SAR=69 data compilations for all leaching column experiments compared with the most sensitive (Sceptre) threshold curves from literature. In general the overall data ranges and behaviors appear similar between the experimental results and literature, with the experimental results ranging from being significantly less sensitive than literature to somewhat more sensitive than literature for each SAR series. This suggests that undisturbed cores from the field, while likely more realistic, exhibit more variable responses to SAR than homogenized repacked soils as used in literature. It is thus important to consider whether generated thresholds curves are intended to be representative of average soils, worst-case soils, or some other statistical representation of the responses of a range of soils.

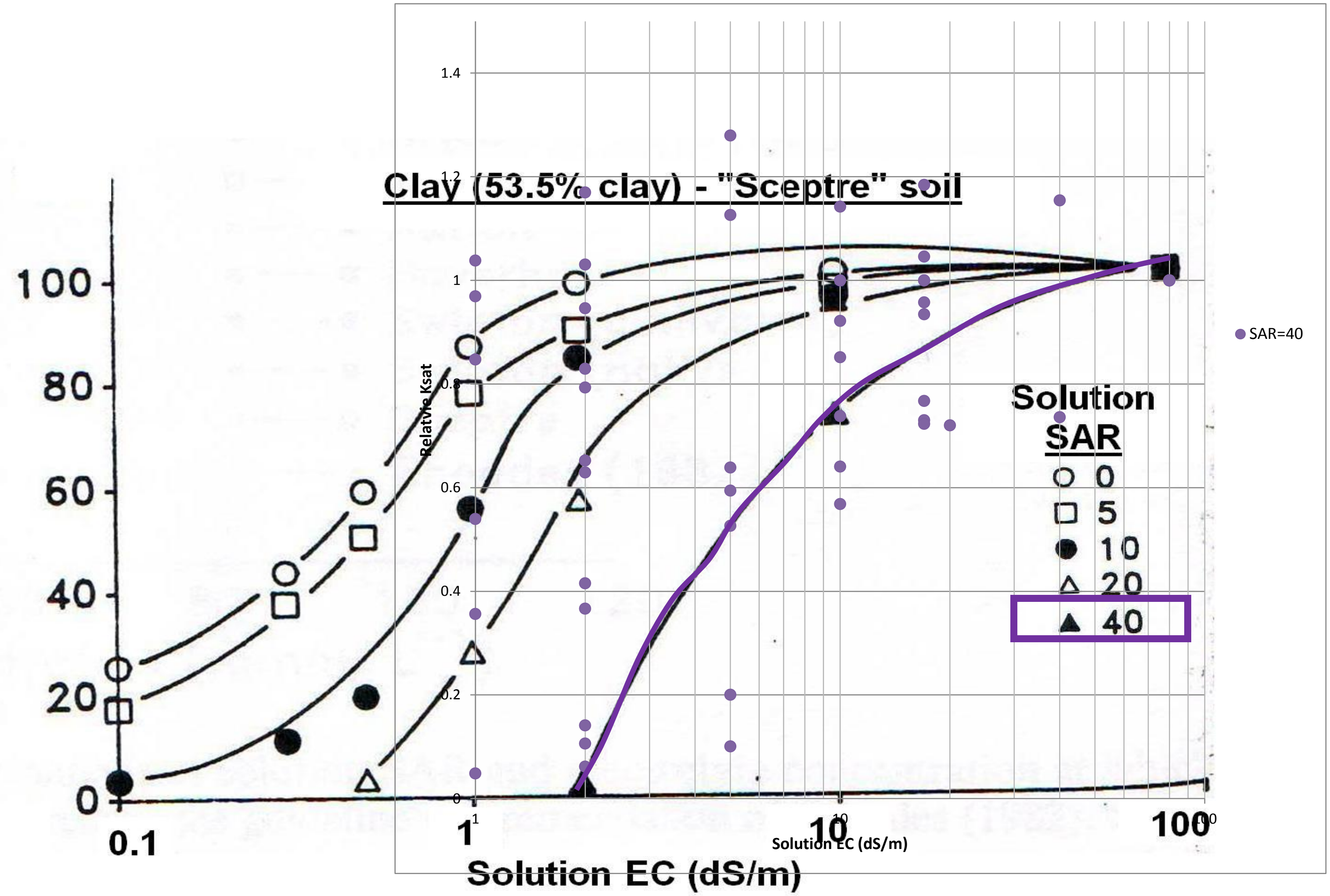
This also raises the general issue of variability in soils, and what statistical representation of soil responses would be appropriate to consider when generating appropriate thresholds and guidelines. For example, two soils with similar soil texture (e.g., clay loam) may differ in their response to SAR-induced K_{sat} losses due to other factors such as degree of compaction, the initial presence of macro-pores, clay type, initial hydraulic conductivity, or other factors such as the degree of shearing/dispersion experienced during the deposition of soils in the field. Soil texture appears to play a large role based on the literature data using homogenized repacked columns, and texture should thus be considered when generating applicable thresholds. It may be beneficial to also consider other factors such as bulk density or (where available) initial hydraulic conductivity when choosing appropriate thresholds.

Figure 5.45. Comparison of leaching column results to "Sceptre" soils: SAR=20



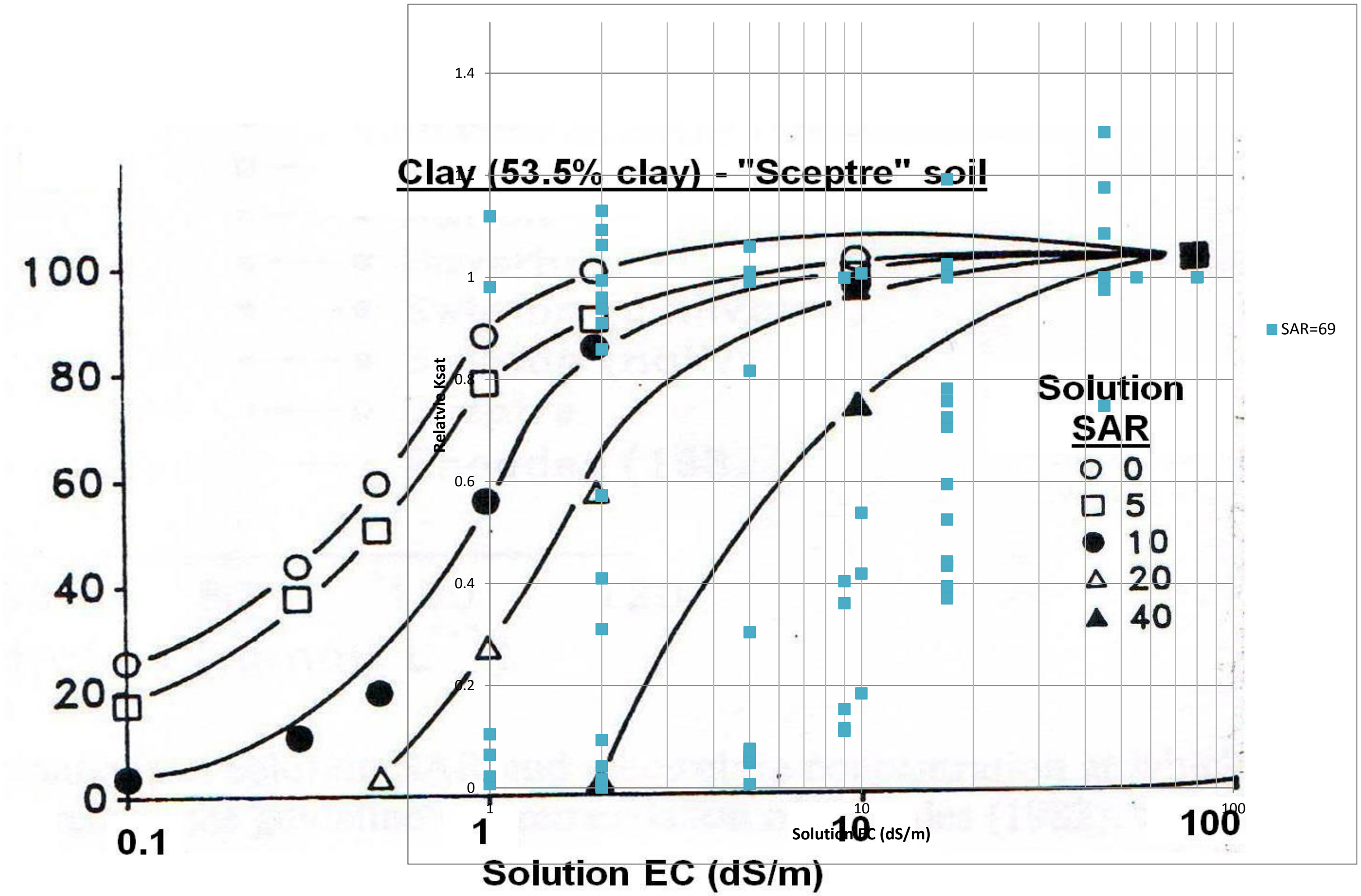
Note: plotted leaching column SAR=20 data in green to be compared to overlain SAR=20 threshold from literature

Figure 5.45. Comparison of leaching column results to "Sceptre" soils: SAR=40



Note: plotted leaching column SAR=40 data in purple to be compared to overlain SAR=40 threshold from literature

Figure 5.46. Comparison of leaching column results to "Sceptre" soils: SAR=69



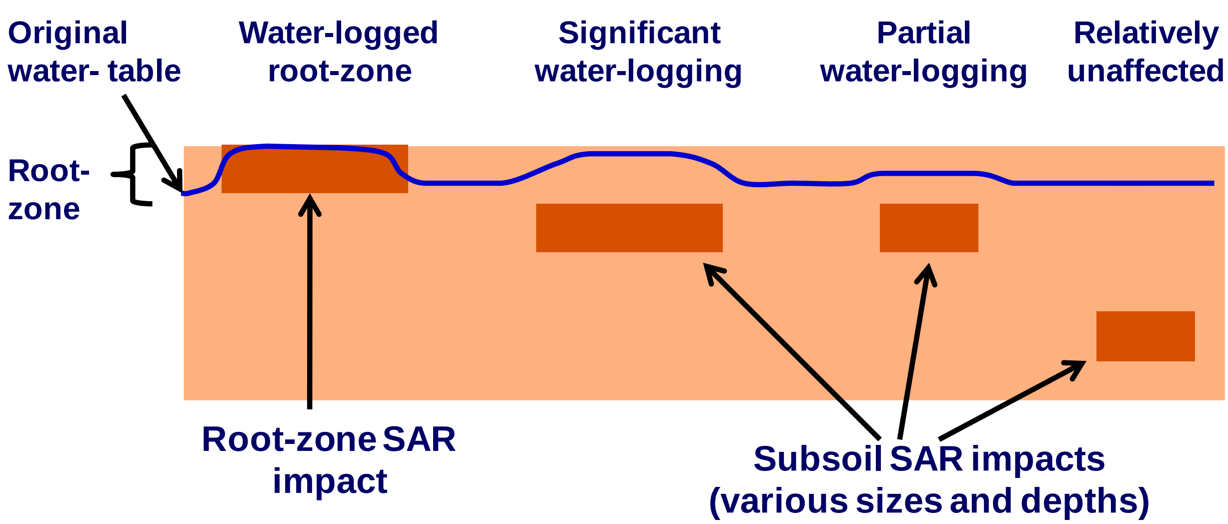
Note: plotted leaching column SAR=69 data in blue does not have a directly comparable threshold from literature, but would be expected to fall to the right of the literature SAR=40 threshold

6 WATER TABLE MODELING

A potential framework for developing subsoil SAR guidelines could involve combining the results from EC/SAR/hydraulic conductivity experiments with an estimation of environmentally-relevant hydraulic conductivity losses for subsoil. As mentioned in Section 1, the primary potential adverse effect of subsoil SAR is creating a shallower water table through reduction in moisture transport through soil. If this shallower water table creates a water-logged root-zone, adverse effects on plant growth may be possible.

Figure 6.1 shows a possible conceptual model for the effects of SAR on water table, which would likely be a function of K_{sat} reduction, infiltration rate, impact size, impact depth, original water table depth, soil texture, and other factors. For example, deeper and smaller impacts likely have less effect on water table whereas shallower and larger impacts may be more likely to have significant effects.

Figure 6.1. Potential Water Table Effects from SAR



6.1 WATER TABLE MODELING – PHASE 1

One way to examine the interaction between these parameters is through three-dimensional transport modeling using a program such as Modflow™. Such a model allows selecting of numerous transport and lithology parameters to create a baseline scenario followed by altering various parameters to evaluate their effects. The baseline model consists of a 3 m water table, 30 mm/year infiltration rate, $1x10^{-8}$ m/s vertical hydraulic conductivity, and a $1x10^{-7}$ m/s horizontal hydraulic conductivity. The baseline scenario has essentially vertical water flow with a flat water table and no lateral flow. Refer to Equilibrium Environmental 2011 for a detailed overview of methods used in this analysis.

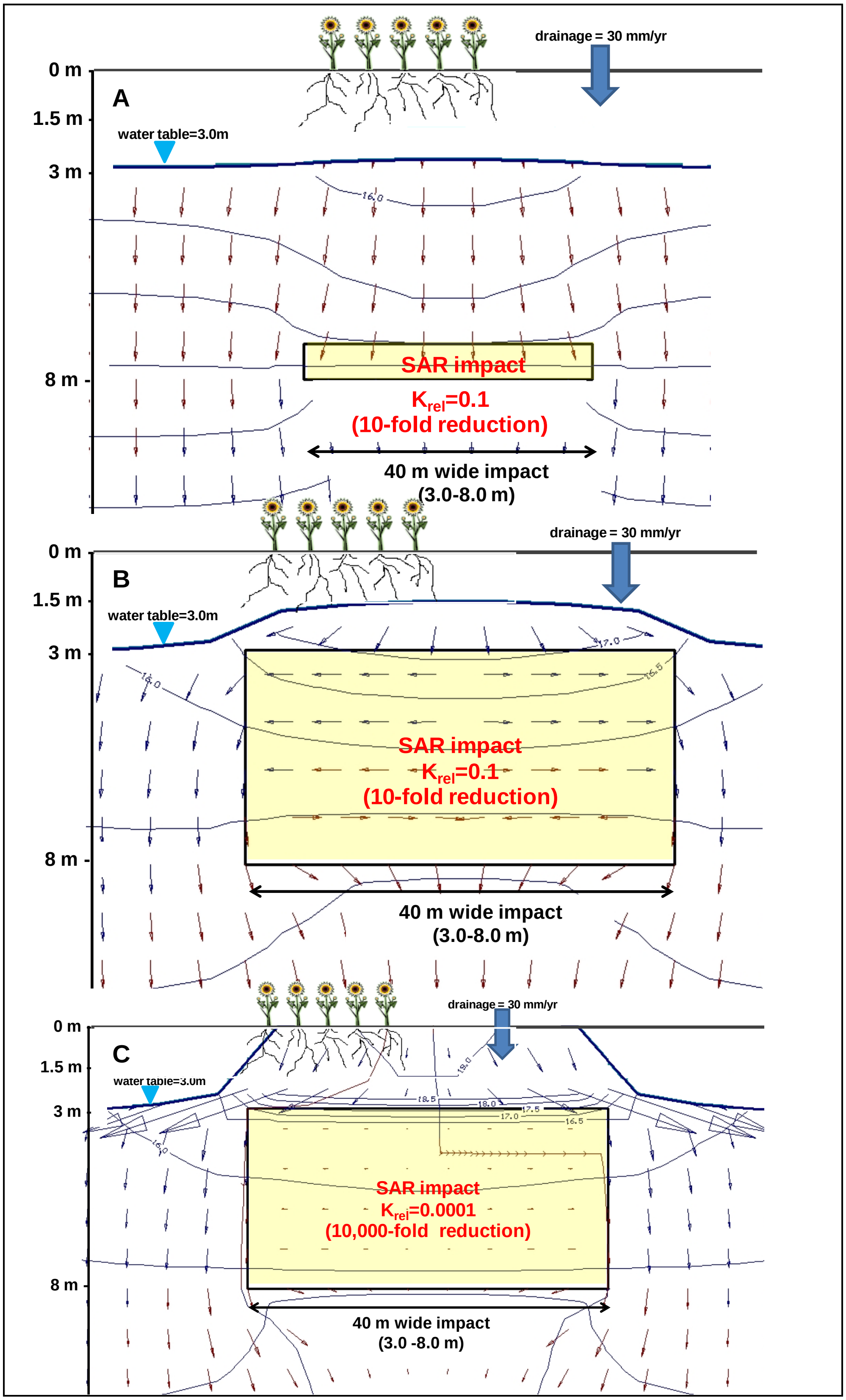
Starting from the baseline scenario, a first model scenario (Figure 6.2A) was created to evaluate the potential effects of a 10-fold (1-order-of-magnitude) K_{sat} reduction in a 40 m wide, 1 m thick impact located at from 7 to 8 m deep. Figure 6.2A shows a slight disturbance in water flow in the vicinity of the SAR impact as water moves through the impact zone at a somewhat slower rate and also flows around the edges laterally. The water table is observed to become somewhat shallower above the impact, but the maximum change in water table depth is less than 0.5 m and does not extend into the assumed 1.5 m root-zone which typically contains the majority of root-mass. This scenario is not considered to represent an adverse effect, especially in the context of seasonal water-table fluctuations which can span 1 m or more in many situations.

Scenario #2 involved creating a thicker (5 m thick) SAR impact with the same 10-fold K_{sat} reduction but occurring over the 3-8 m depth interval (Figure 6.2B). A more visible disturbance in water flow is observed in the vicinity of the SAR impact, with more water traveling around the impact due to the increased restriction to flow through the impact. The modeled water table became shallower by 1-1.5 m, approaching the root-zone located at 1.5 m. However, this scenario still does not represent an apparent adverse effect in terms of creating a water-logged root-zone, but is clearly nearer to such a threshold than scenario #1 was.

To examine a potentially severe SAR impact, scenario #3 (Figure 6.2C) simulated a 10,000-fold (4-order-of-magnitude) K_{sat} reduction over the 3-8 m depth interval. Figure 6.2C shows results from this scenario, showing a significant reduction in water table depth and water-logging of the root-zone. Compared to scenario #2, water was largely unable to penetrate through the thick SAR impact and thus required a complete reliance on lateral transport. While this lateral transport was able to minimize effects on water table near the edge of the 40 m wide impact, the effects were more significant toward the center of the impact. This provides an initial indication of the influence of impact size on potential water table effects, and could be examined in more detail in future studies.

Overall, subsoil K_{sat} reductions of 10- to 100-fold appear to be tolerated in many model scenarios without causing significant water-logging of root-zone soils. This is especially true of deeper, smaller impacts or in cases with deeper water tables. Additional model scenarios evaluating a broader range of conditions could help refine the understanding of what magnitude of K_{sat} reductions in subsoils could result in adverse root-zone effects.

Figure 6.2. Water table modeling of SAR effects at A) 10-fold K_{sat} reduction at 8 m depth, B) 10-fold K_{sat} reduction at 3 m depth, and C) 10,000-fold K_{sat} reduction at 3 m depth



6.2 WATER TABLE MODELING – PHASE 2

6.2.1 Influence of vertical gradient

Phase 2 water table modeling experiments explored the effect of vertical gradient on the potential for SAR impacts to raise the water table. Figure 6.3 shows that minimal effects on the water table are predicted for SAR impacts at vertical gradients of 0.02. In contrast, potentially significant SAR impacts can result from larger original vertical gradients (Figure 6.4). Therefore, the original vertical gradient appears to influence the potential for SAR-induced root-zone water-logging.

Figure 6.3. SAR impacts modeled for K_{sat}=4-fold reduction at vertical gradient =0.02

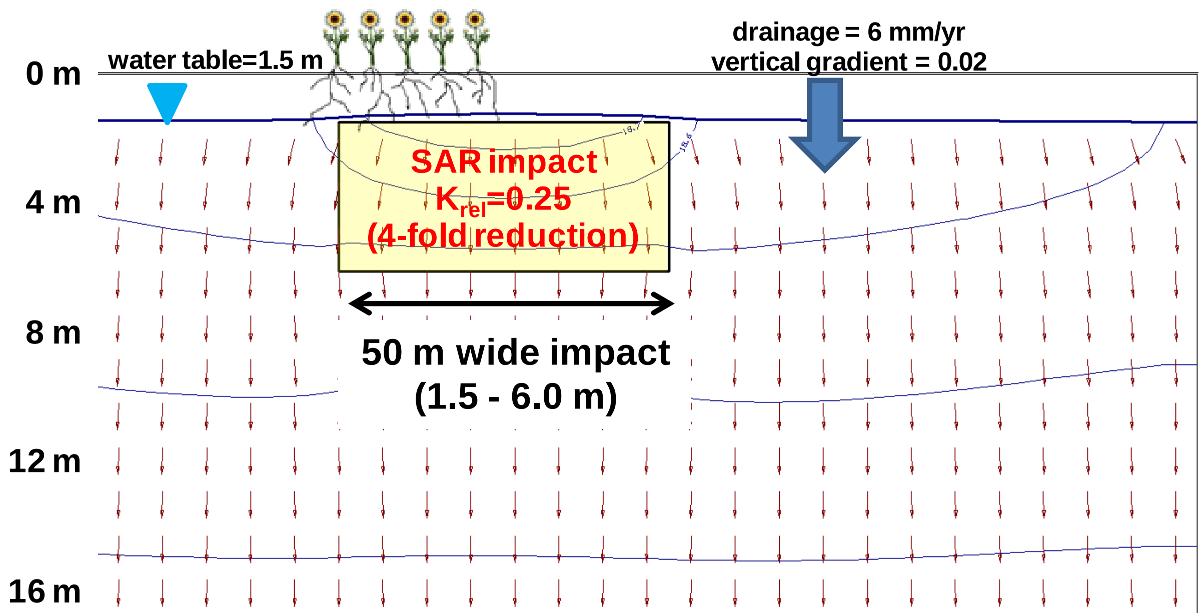
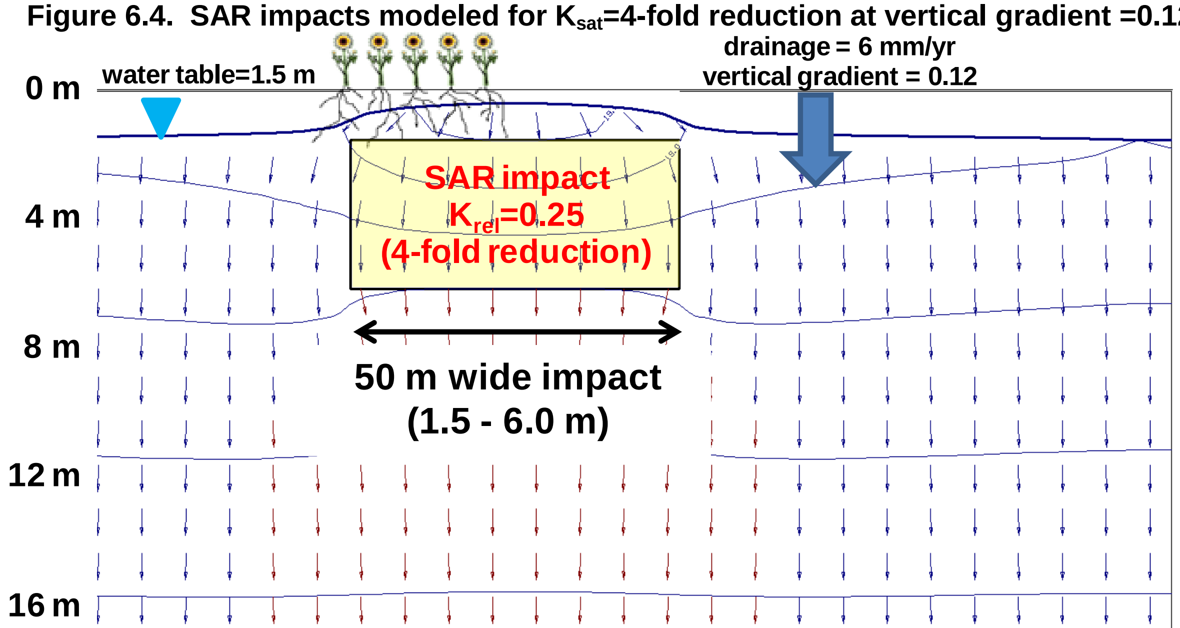


Figure 6.4. SAR impacts modeled for K_{sat}=4-fold reduction at vertical gradient =0.12



Figures 6.5 and 6.6 show another example of the influence of vertical gradient on the consequences of SAR impacts on water table level. Again, minimal effects from SAR impacts are predicted for vertical gradients of 0.02 while more significant impacts result at larger gradients (0.12).

Figure 6.5. SAR impacts modeled for K_{sat}=10-fold reduction at vertical gradient =0.02

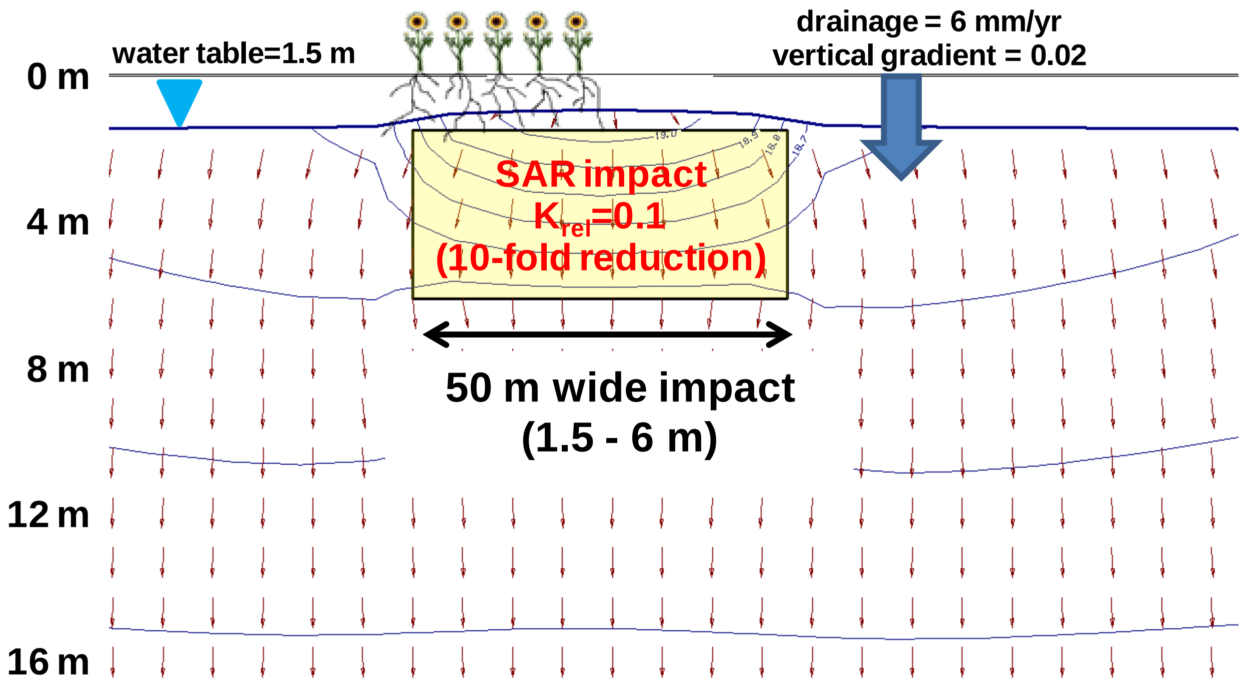
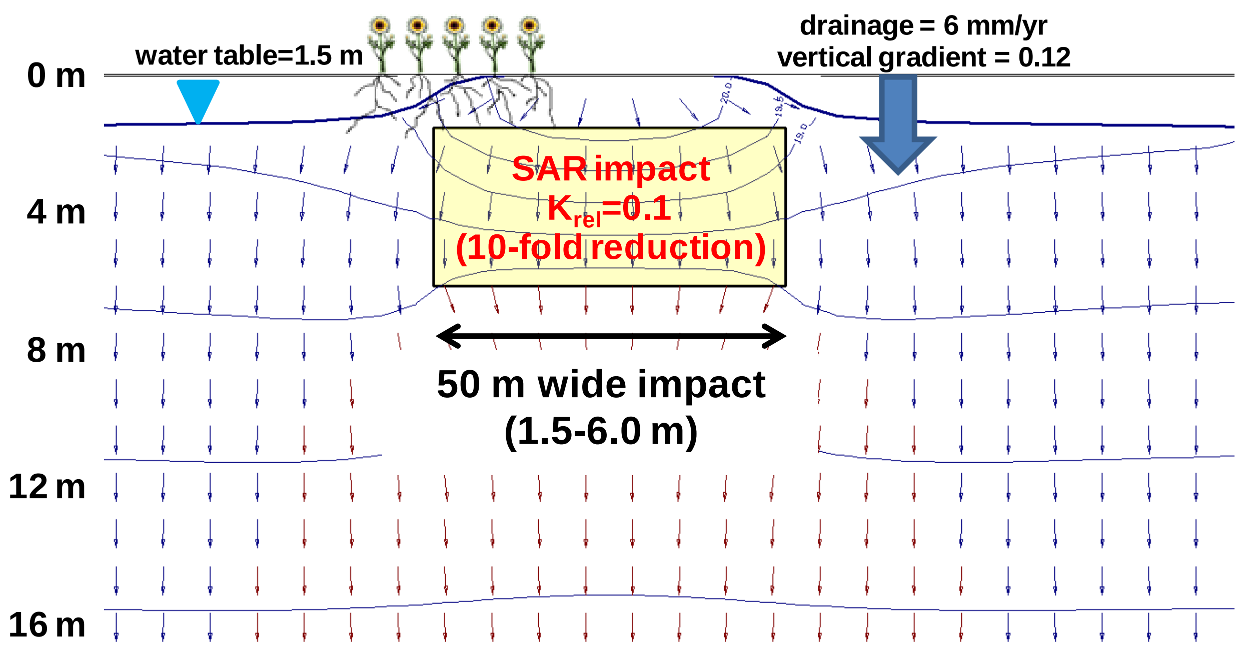


Figure 6.6. SAR impacts modeled for K_{sat}=10-fold reduction at vertical gradient = 0.12



6.2.2 Influence of impact dimensions

Impact dimensions also play a key role in determining the magnitude of SAR effects on the water table. Figures 6.7 and 6.8 show that a larger SAR impact area corresponds to a greater effect on the water table level, with a 100 m impact showing more influence than a 15 m impact. This is likely related to the increased ability for water to travel laterally around smaller impacts.

Figure 6.7. Modeling the effects of a large SAR impact area on the water table

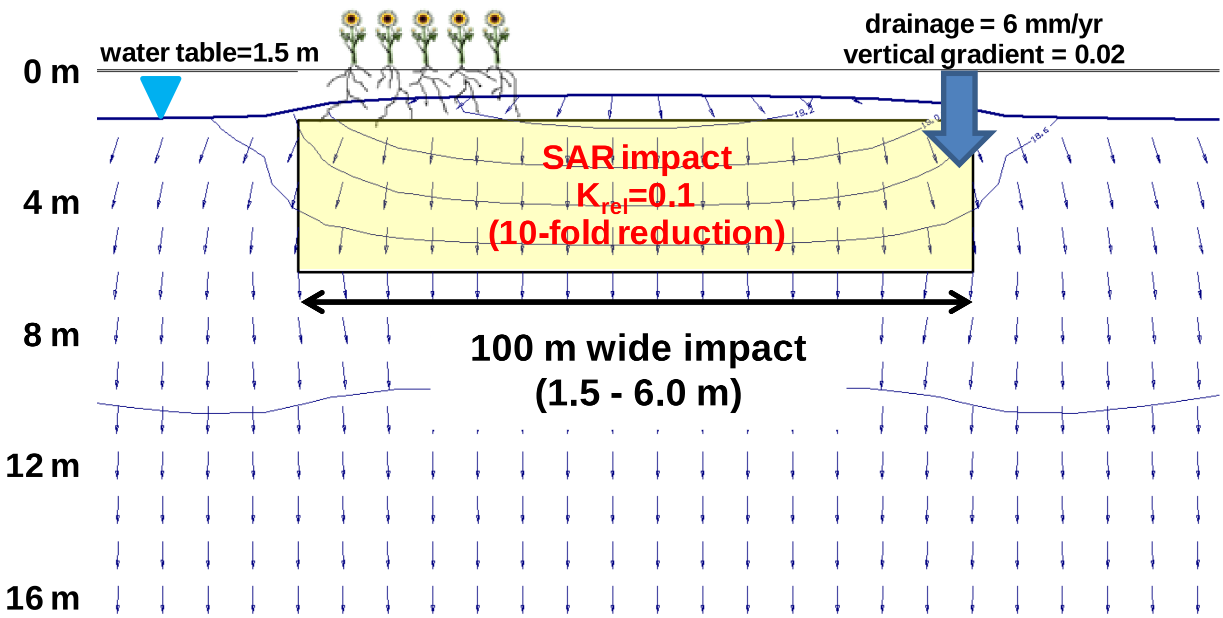
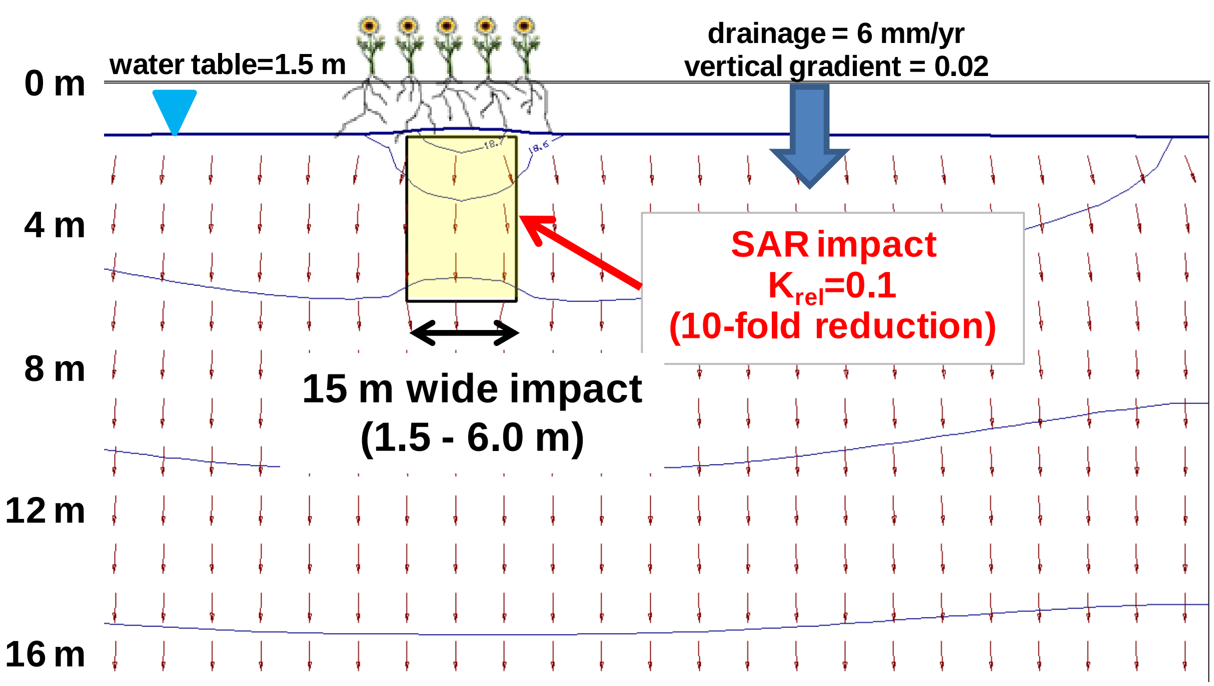


Figure 6.8. Modeling the effects of a small SAR impact area on the water table



6.2.3 Influence of magnitude of K_{sat} reductions

The following series of four water table models below (Figures 6.9-6.12) show that the effects of SAR impacts on water table level are greater with larger K_{sat} reductions. Generally, as the hydraulic conductivity of an impacted zone decreases, its impact on the water table increases.

Figure 6.9. Modeling the effect of 2-fold K_{sat} reductions on the water table level

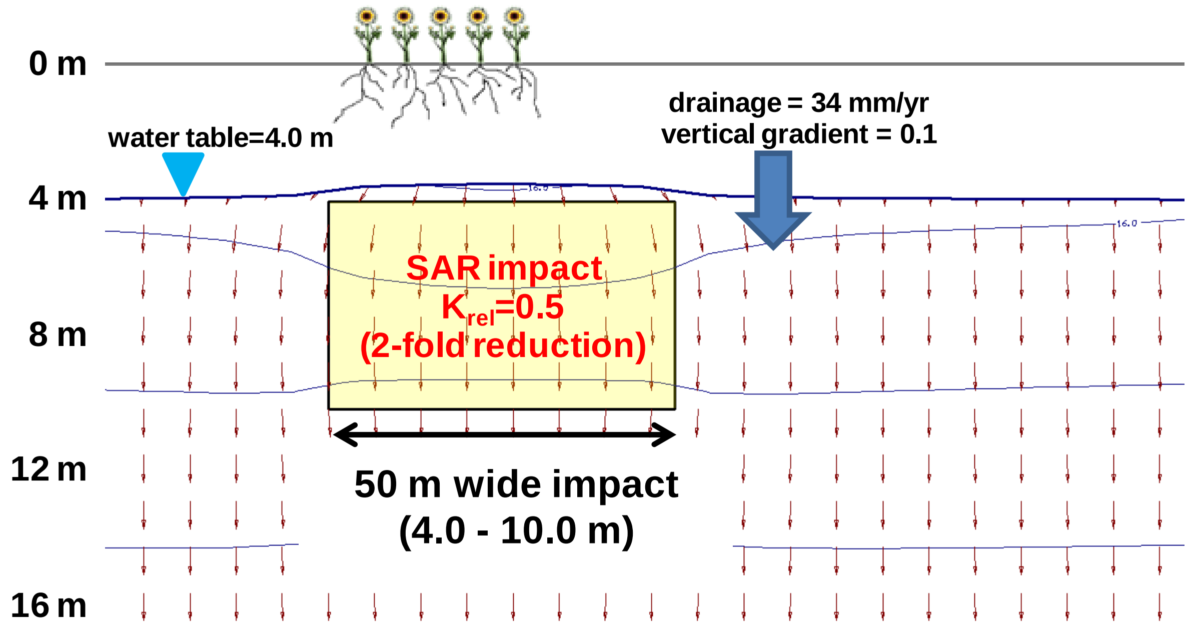


Figure 6.10. Modeling the effect of 4-fold K_{sat} reductions on the water table level

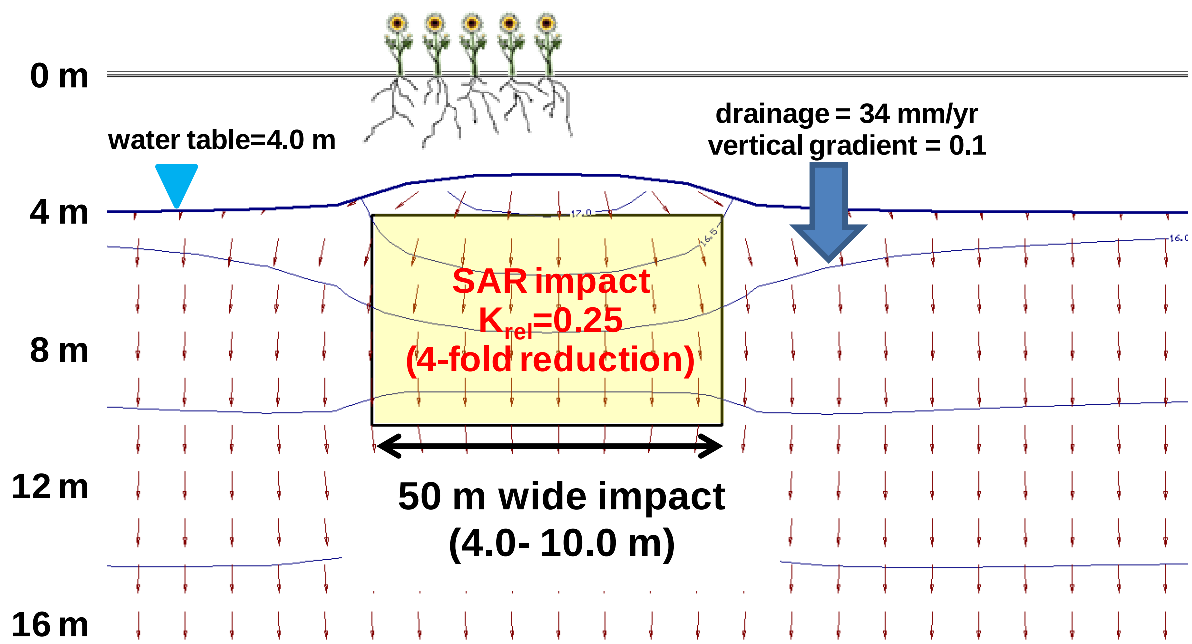


Figure 6.11. Modeling the effect of 10-fold K_{sat} reductions on the water table level

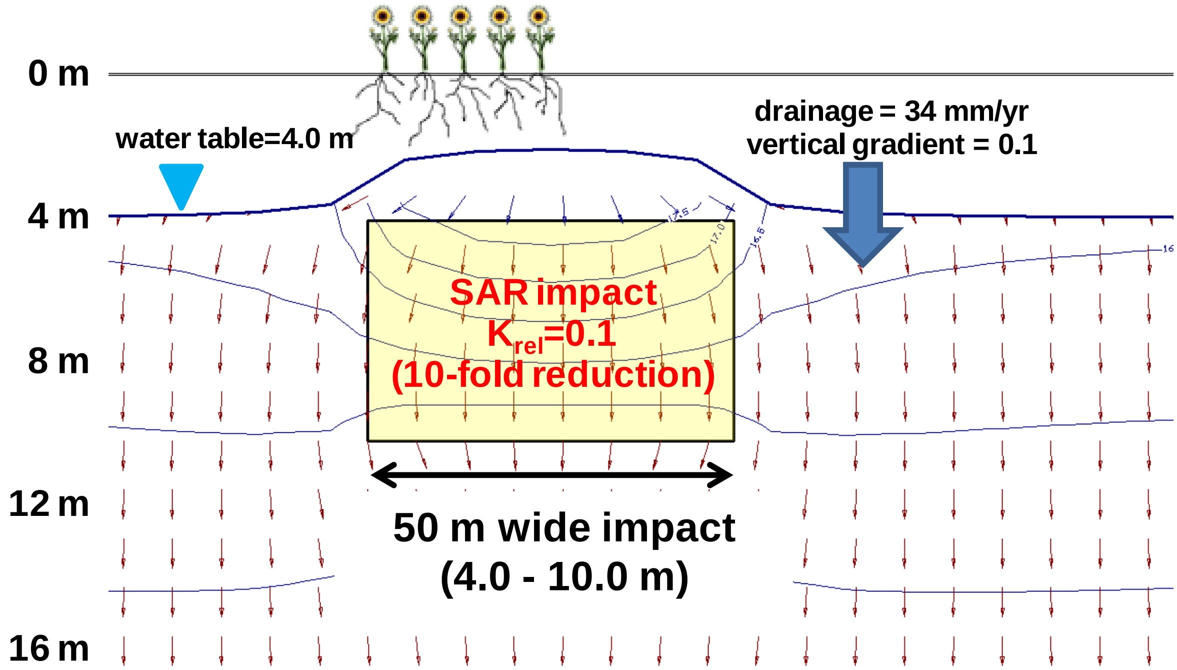
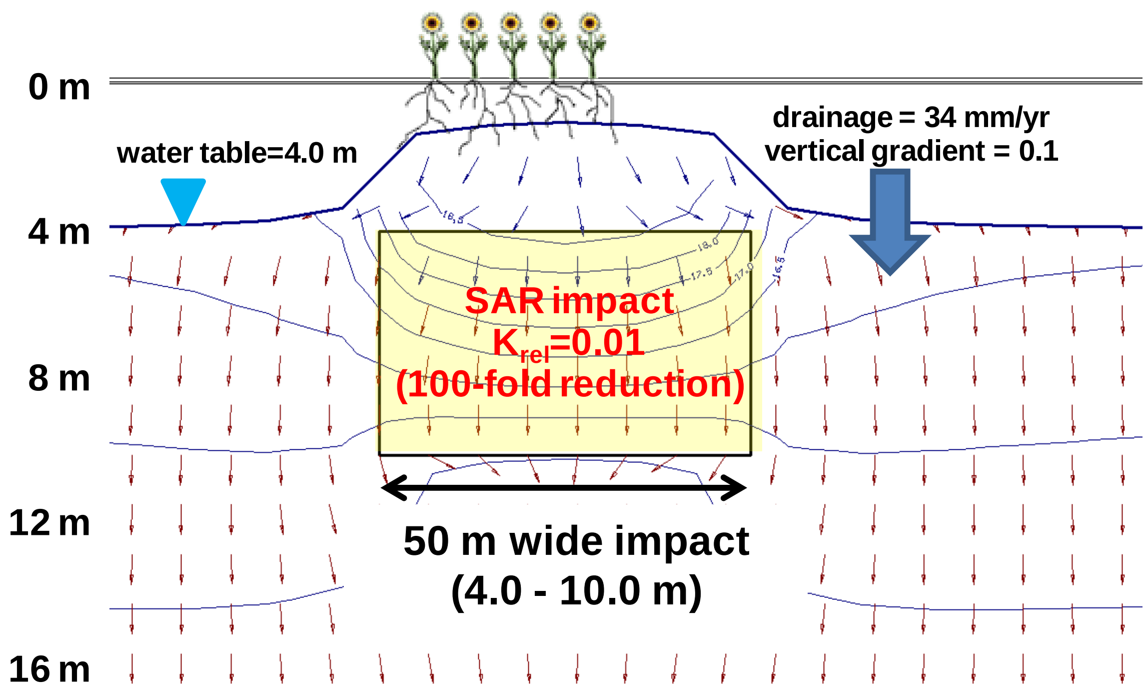


Figure 6.12. Modeling the effect of 100-fold K_{sat} reductions on the water table level



6.3 WATER TABLE MODELING SUMMARY

The results from a series of relatively high-risk model scenarios are shown below (Table 6.1). These tests simulated the effects of SAR impacts right below the root-zone (1.5-6.0m) and assumed a shallow water table (1.5m). General trends observed include roles for vertical gradient, impact dimensions, and K_{sat} loss influencing the extent of SAR impact on water table. In some cases with very high initial vertical gradient (0.12) and higher K_{sat} losses, the water table was predicted to become even shallower than 1.0 meter. In general, lesser water table effects were observed using the more typical vertical gradient of 0.02.

Table 6.1. Parameters tested and results for all water table modeling experiments

Inputs					Outputs	
Impact dimensions	**Impact depth range**	**Drainage rate**	**Initial water table depth**	**Krel**	**Impacted water table (m)**	
(m)	**(m)**	**(mm/yr)**	**(m)**		**vert grad=0.12**	**vert grad=0.02**
100 x 100	1.5 - 6 m	6	1.5	1.0	**1.4**	**1.4**
100 x 100	1.5 - 6 m	6	1.5	0.75	**1.2**	**1.4**
100 x 100	1.5 - 6 m	6	1.5	0.50	**0.9**	**1.3**
100 x 100	1.5 - 6 m	6	1.5	0.25	**0**	**1.2**
100 x 100	1.5 - 6 m	6	1.5	0.1	**0**	**0.8**
75x75	1.5 - 6 m	6	1.5	1.00	**1.4**	**1.4**
75x75	1.5 - 6 m	6	1.5	0.75	**1.2**	**1.4**
75x75	1.5 - 6 m	6	1.5	0.25	**0.2**	**1.2**
50x50	1.5 - 6 m	6	1.5	0.75	**1.2**	**1.4**
50x50	1.5 - 6 m	6	1.5	0.50	**0.9**	**1.35**
50x50	1.5 - 6 m	6	1.5	0.25	**0.4**	**1.2**
50x50	1.5 - 6 m	6	1.5	0.10	**0**	**1.0**
25x25	1.5 - 6 m	6	1.5	0.75	**1.3**	**1.4**
25x25	1.5 - 6 m	6	1.5	0.50	**1.2**	**1.3**
25x25	1.5 - 6 m	6	1.5	0.25	**0.8**	**1.3**
25x25	1.5 - 6 m	6	1.5	0.10	**0.4**	**1.2**
25x25	1.5 - 6 m	6	1.5	0.01	**0**	**1.0**
15x15	1.5 - 6 m	6	1.5	0.75	**1.3**	**1.4**
15x15	1.5 - 6 m	6	1.5	0.50	**1.2**	**1.4**
15x15	1.5 - 6 m	6	1.5	0.25	**1.0**	**1.4**
15x15	1.5 - 6 m	6	1.5	0.10	**0.7**	**1.3**
15x15	1.5 - 6 m	6	1.5	0.01	**0.5**	**1.1**

7 INITIAL SUBSOIL SAR GUIDELINE RECOMMENDATIONS

Due to the large number of variables identified which influence SAR effects on water transport, it is recommended that subsoil SAR guidelines be implemented within the context of the Alberta Environment 'Subsoil Salinity Tool' (SST). This allows tailoring of guidelines to site-specific conditions while maintaining a consistency of analysis from site-to-site without the need for a complex, data-intensive site-specific risk assessment for each site.

Subsoil SAR guidelines generated in this manner would generally apply to subsoils below the root-zone, and not the root-zone itself where SCARG (Alberta Environment, 2001) typically applies. Subsoil chloride protocols from the SST could be modified as appropriate to generate site-specific guidelines for subsoil SAR for various receptors outlined below.

7.1 PATHWAYS FOR SUBSOIL SAR GUIDELINE DEVELOPMENT

Potential pathways which could be considered during the implementation of subsoil SAR guidelines into the SST include:

a) Current-day risk to soil structure (related to K_{sat} loss)
b) Future risk to soil structure (due to further leaching of EC from SAR impacts)
c) Upward migration of subsoil SAR back into the root-zone
d) Dugout pathway: irrigation water
e) Dugout pathway: livestock water
f) Aquatic life pathway
g) DUA pathway

The first two of these pathways are unique to subsoil SAR, whereas the other five pathways are consistent with the current SST pathways for chloride. Most of these potential pathways for subsoil SAR could be evaluated based on meeting appropriate Tier 1 guidelines at each receptor, though several of them have differences in how they may be implemented in the SST for SAR/sodium instead of chloride.

Each of these pathways is discussed below, including a discussion of potential methods to implement guidelines in the SST. Key policy issues are also identified in each case which require further discussion with various stakeholders such as Alberta Environment and the PTAC Salinity Working Group in order to clarify aspects of the guideline implementation.

7.1.1 Current-day risk to soil structure (related to K_{sat} loss)

SAR/EC threshold curves allow for evaluation and comparison of site impacts and are originally based on solution (pore water) SAR/EC values from laboratory experiments which then get converted to a saturated paste basis for comparison to field soil results. Figure 7.1 shows an example of various literature thresholds on a solution basis, shown for both 'Willows' and 'Sceptre' soils from Curtin, 1994c. Extrapolations to higher EC/SAR values are also shown, and appear to follow power functions with exponents of approximately 0.55-0.65. It is noteworthy that this exponent is similar to the 0.5 (square-root) used in the denominator of the SAR equation.

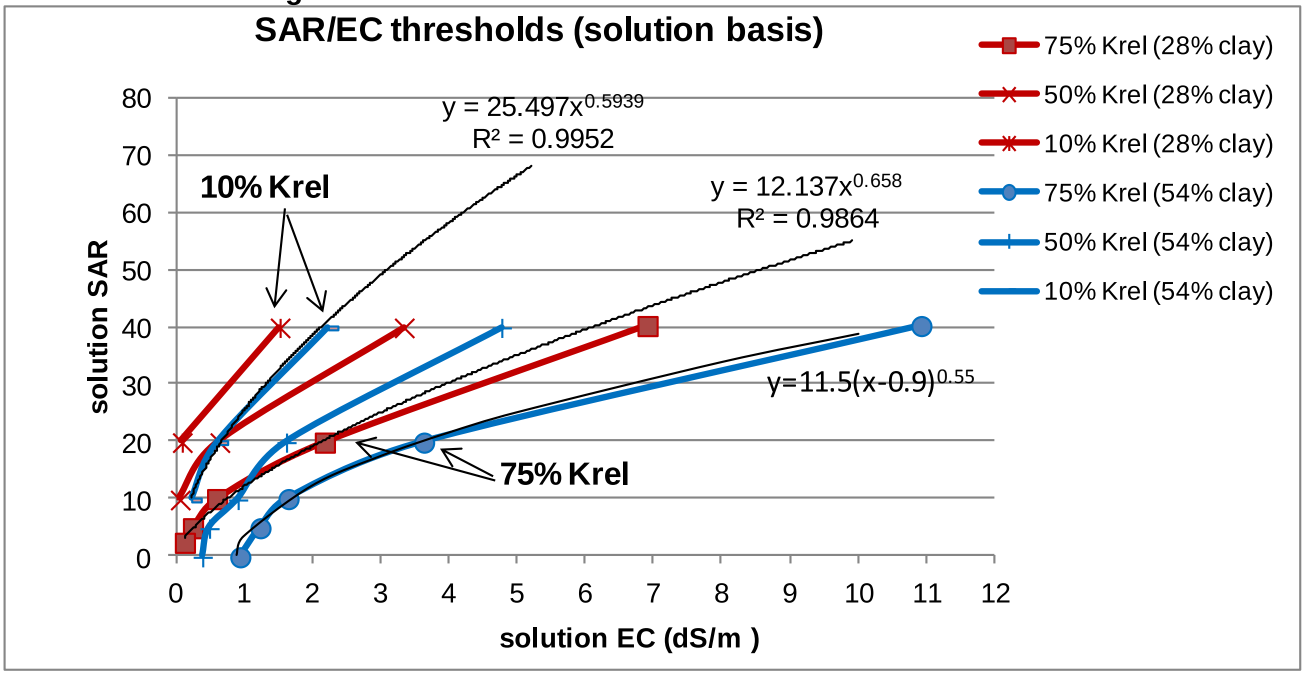
An approximate ratio for the reduction in EC on a saturated paste basis compared to soil solution basis ("EC ratio") can be obtained by the comparing moisture content of the two states. In soil solution (pore water), a soil:water ratio of approximately 4.25:1 is obtained using typical SST defaults for fine soil (bulk density of 1.62 and total porosity of 0.381) shown in Table 7.1 below. If this is compared to the 2:1 soil:water ratio implied by an assumed 50% saturation percentage, an estimated EC ratio of 2.1:1 is obtained. This indicates that the EC on a saturated paste basis would be approximately 2.1-fold lower than on a soil solution basis.

Table 7.1. Default SST soil properties for fine and coarse soils

Parameters	Fine Texture (Clay Content > 18%)	Coarse Texture (Clay Content < 18%)
Bulk Density (g/cm^3)	1.620	1.685
Ksat (mm/d)	0.79	422
Dispersivity (mm)	100	100
Porosity	0.381	0.357

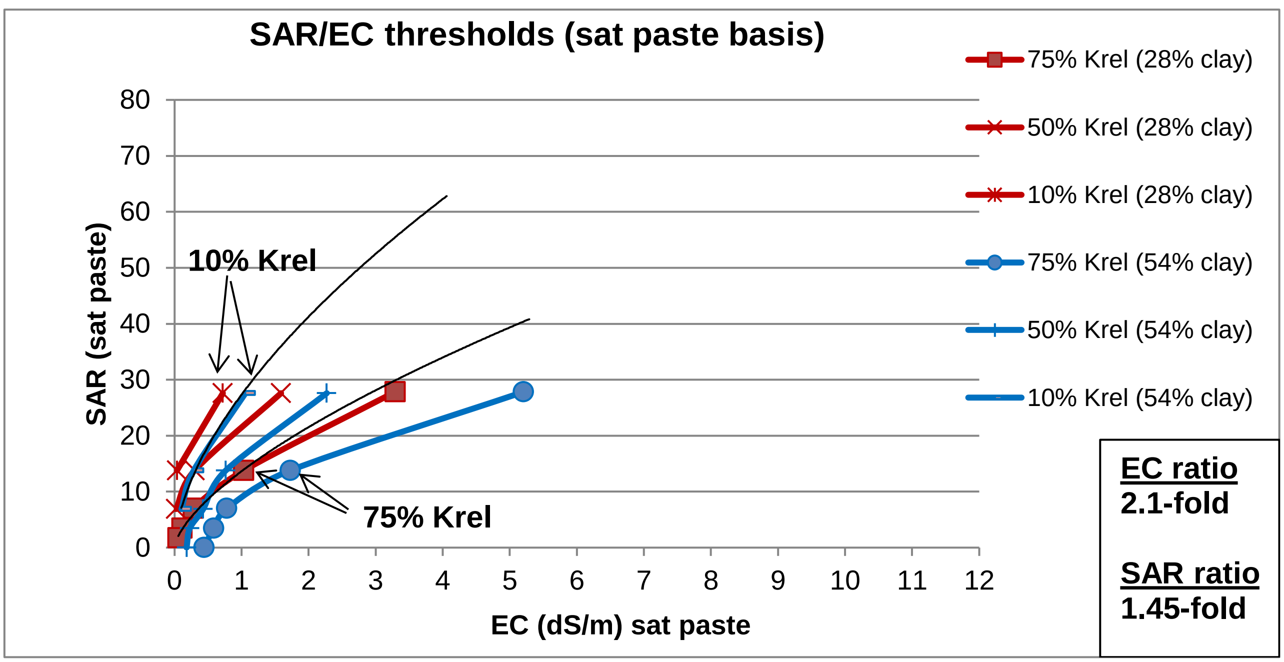
Calculating the reduction in SAR on a saturated paste basis is more complex. A conservative method is to assume SAR is reduced by the square-root of the EC ratio due to the simple proportional reduction of all cations followed by recalculating SAR (which include a square-root in the denominator). This would result in an estimated SAR ratio of 1.45:1 for the above EC ratio of 2.1:1, indicating that SAR would be reduced by 1.45-fold when EC is reduced by 2.1-fold. The effect of such an assumption is shown in Figure 7.2, whereby solution thresholds from Figure 7.1 are recalculated on a saturated paste basis using this EC ratio of 2.1 and SAR ratio of 1.45. Extrapolations of the saturated paste thresholds retain the similar 0.55-0.65 exponent as the solution thresholds.

Figure 7.1. SAR/EC threshold curves on a solution basis



Note: Extrapolations to higher EC/SAR values follow power functions with exponents of ~0.55-0.65

Figure 7.2. Sat paste threshold curves (assuming a 2.1 EC ratio and 1.45 SAR ratio)



Note: sat paste thresholds above assume a 2.1-fold ratio for converting from solution EC to saturated paste EC, and a 1.45-fold ratio (square root of 2.1) for converting from solution SAR to sat paste SAR (likely conservative, does not consider cation exchange reactions). Extrapolations to higher EC/SAR values follow power functions with exponents of ~0.55-0.65

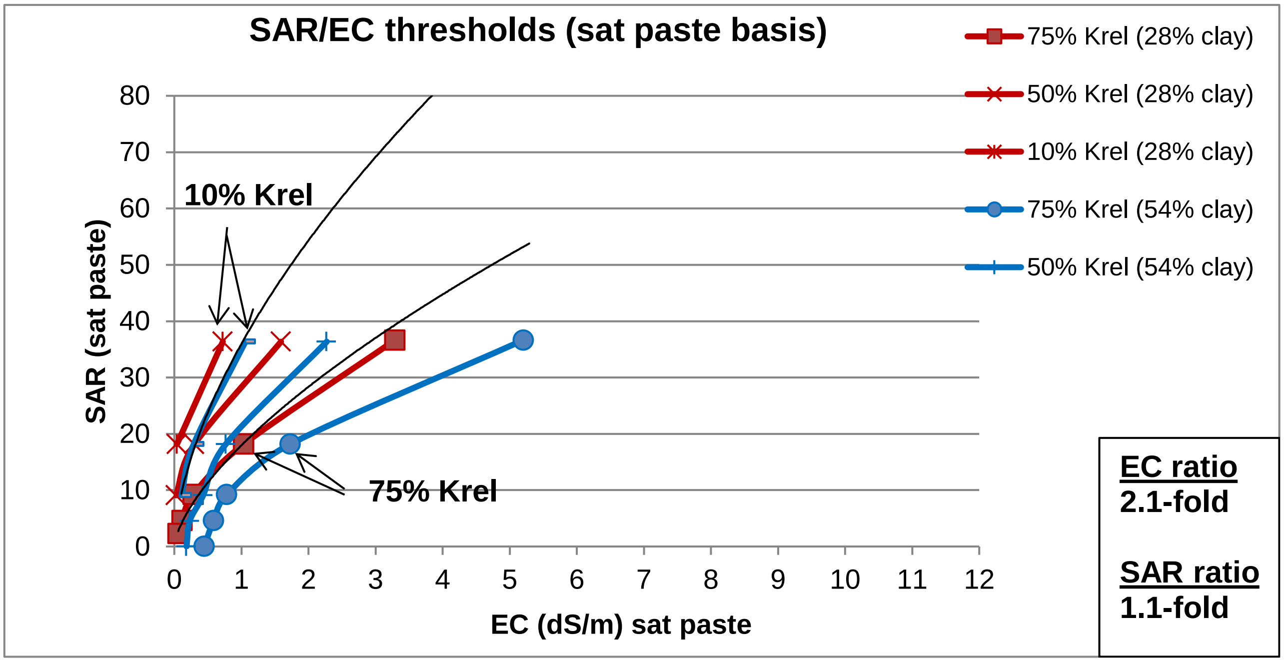
The method described above does not consider any cation exchange effects as soil is converted from soil solution basis to a saturated paste basis, and represents a likely conservative scenario. 'Cation Exchange Capacity' (CEC) provides a large pool of reversibly sorbed cations on soil surfaces, particularly on clay and organic matter. Typical Alberta soils have CECs of 100 to >250 meq/kg whereas a typical clay loam reference soil has a CEC of approximately 180 meq/kg. Therefore, in order to have comparable cations in solution, approximately 30 dS/m of additional Na or Ca is required. Exchanged cations are thus often significantly higher than dissolved cations, producing an effect of providing a buffer against changes in SAR by re-establishing equilibrium. This would result in saturated paste SAR values remaining more similar to solution SAR values than predicted by the square root method.

This cation exchange process was modeled with the salinity version of the LEACHM modeling program ("LEACHC"), which showed a typical SAR ratio of 1.1 to 1.2 (or less) due to cation exchange when converting from solution to saturated paste. The effects of a fixed SAR ratio such as 1.1 are shown in Figure 7.3, which shows thresholds assuming the same EC ratio of 2.1 but now a fixed SAR ratio of 1.1. This results in threshold curves which are approximately 33% higher, thus suggesting less risk to soils for a given solution EC/SAR.

If the more conservative square-root method were to be used for generating SAR ratios, some inherent safety margin would thus be predicted when compared to the likely more-realistic scenario involving cation exchange. Figure 7.4 shows an example of such a safety margin by comparing the 10-fold K_{sat} reduction thresholds for Sceptre (54% clay) soils using the two SAR ratios of 1.45 vs 1.1. Such a safety margin could potentially serve to accommodate future reductions in EC/SAR values due to leaching with background salinity, since EC is likely to reduce at a faster rate than SAR. This future leaching of EC and SAR by background salinity is considered in the section below.

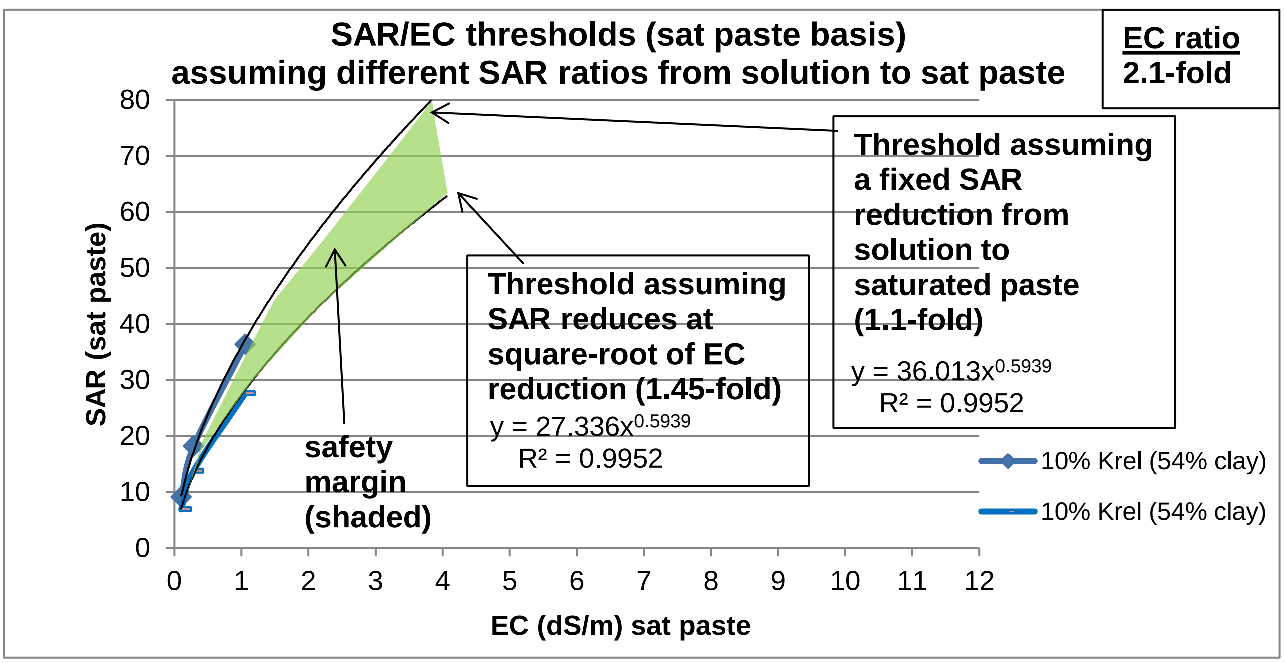
Regardless of which method of generating a SAR ratio is used, it is necessary to also define an acceptable K_{sat} reduction threshold to compare to site impacts. Acceptable K_{sat} reductions of approximately 10-fold appear to be tolerated in many cases based on water table modeling, and could provide an initial baseline threshold for further discussions. This 10-fold threshold could potentially be used exclusively, or tailored upwards and/or downwards based on site-specific parameters such as water table depth, impact depth, impact dimensions, soil clay content, or other factors. These threshold curves could be based on the literature leaching column work on Saskatchewan soils (Curtin, 1994c) since they appear to be sufficiently representative of Alberta soils based on the Alberta leaching column experiments in this research. It is beneficial that the literature Curtin curves are based on sensitive Saskatchewan soils which are typically similar to Alberta soils in terms of clay type, with the typical composition of Alberta clays being 2:1 smectites which are also known to be swelling/dispersive soils. To help further refine the response to SAR and define appropriate thresholds, it would likely be beneficial to consider the clay content of the site soils, possibly in terms of three or more general ranges of clay content.

Figure 7.3. Sat paste threshold curves (assuming a 2.1 EC ratio and 1.1 SAR ratio)



Note: sat paste thresholds above assume a 2.1-fold ratio for converting from solution EC to saturated paste EC, and a fixed 1.1-fold ratio for converting from solution SAR to sat paste SAR (from modeling considering cation exchange reactions). Extrapolations to higher EC/SAR values follow power functions with exponents of 0.55-0.65

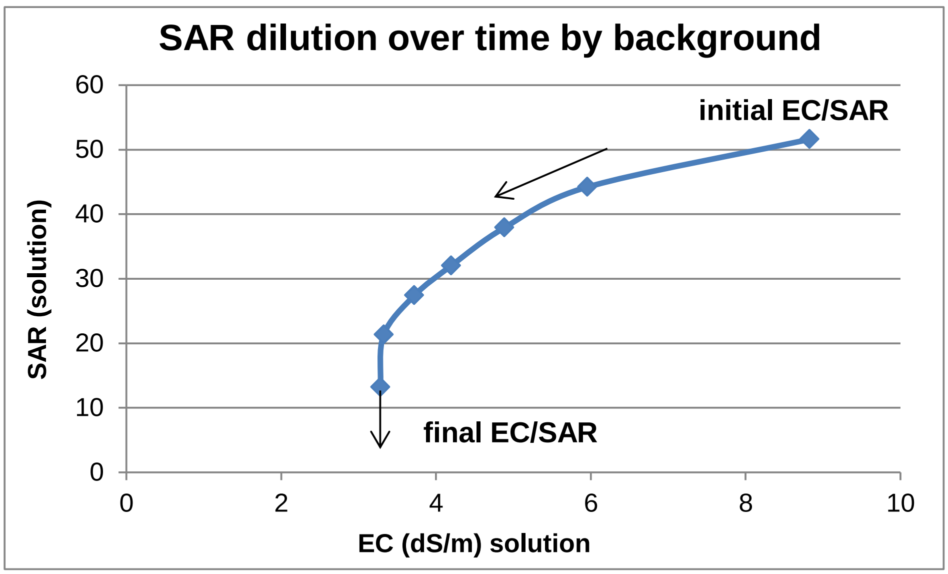
Figure 7.4. Sat paste thresholds assuming different SAR ratios



7.1.2 Future leaching of EC/SAR by background

Current SAR/EC combinations may be acceptable, but both EC and SAR may be diluted in the future by leaching with background salinity. EC leaches faster than SAR, and SAR 'traces' are often left behind as historical salt impacts. The relative rate of EC and SAR leaching is dependent on the original SAR/EC and CEC as well as the composition of the leaching water (usually from backfill which contains dissolved ions). Future leaching of EC/SAR was modeled using LEACHC, and showed a reduction of EC/SAR over time (Figure 7.5) as initial impacts (solution SAR~50, solution EC~9) are diluted with background salinity (solution SAR~2.5, and solution EC of ~3.1). This is comparable to a background saturated paste EC of 1.5 dS/m and SAR of 2, and is highly relevant to scenarios where impacted root-zone soils are excavated and backfilled while leaving subsoil SAR impacts in-place below the root-zone. SAR/EC impacts were modeled to reduce toward background concentrations, not towards zero, and EC reached background conditions faster than SAR.

Figure 7.5. Modeling dilution of SAR over time by background concentrations



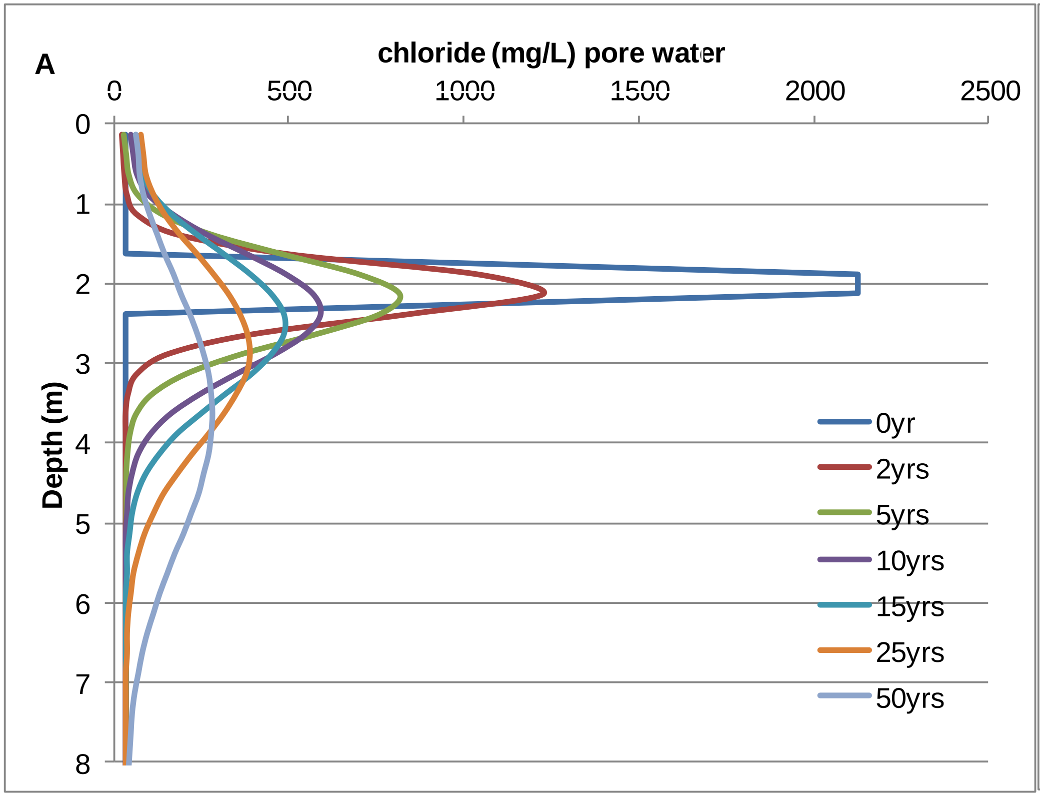
This general shape of future EC/SAR reductions does not appear to be significantly worse than the shape of the EC/SAR thresholds, especially when using the more conservative square-root method for estimating SAR ration between soil solution and saturated paste. Thus, this more conservative square-root method may be an appropriate choice in that it provides some additional protection (safety margin) against future reductions in EC/SAR.

7.1.3 Upward migration of SAR into root-zone

SAR may potentially migrate from impacted subsoil up into the root-zone, such as in scenarios where highly elevated SAR remains in subsoil after excavating the root-zone and backfilling with clean fill. This is more likely to cause potential future SAR exceedances in the root-zone in locations with low background EC and SAR values. This upward migration likely occurs more slowly than chloride based on field data which consistently shows SAR impacts lagging behind the chloride impacts. This is likely due to cation exchange reactions, where portions of the transported sodium impacts become exchanged onto the cation exchange complex and thus require additional time (and sodium) to transport further.

Figure 7.6 shows a modeled LEACHC example of this SAR retardation effect, whereby a 0.5 m thick layer of sodium chloride impacts are modeled to have the sodium, portion migrate both upward and downward at a slower rate than chloride. Peak SAR breakthrough in the root-zone is also less than chloride, with Figure 7.7 showing that SAR impacts peak more slowly and with less relative concentration than chloride (14% of the initial peak for SAR compared to 24% of the initial peak for chloride). Upward SAR risk to root-zone could thus potentially be modeled using similar SST protocol based on drainage rate, background SAR/EC, and other factors, potentially with some additional adjustments to account for this retardation / attenuation effect.

Figure 7.6. Modeling the upward migration of chloride (A) and SAR (B) into the root-zone



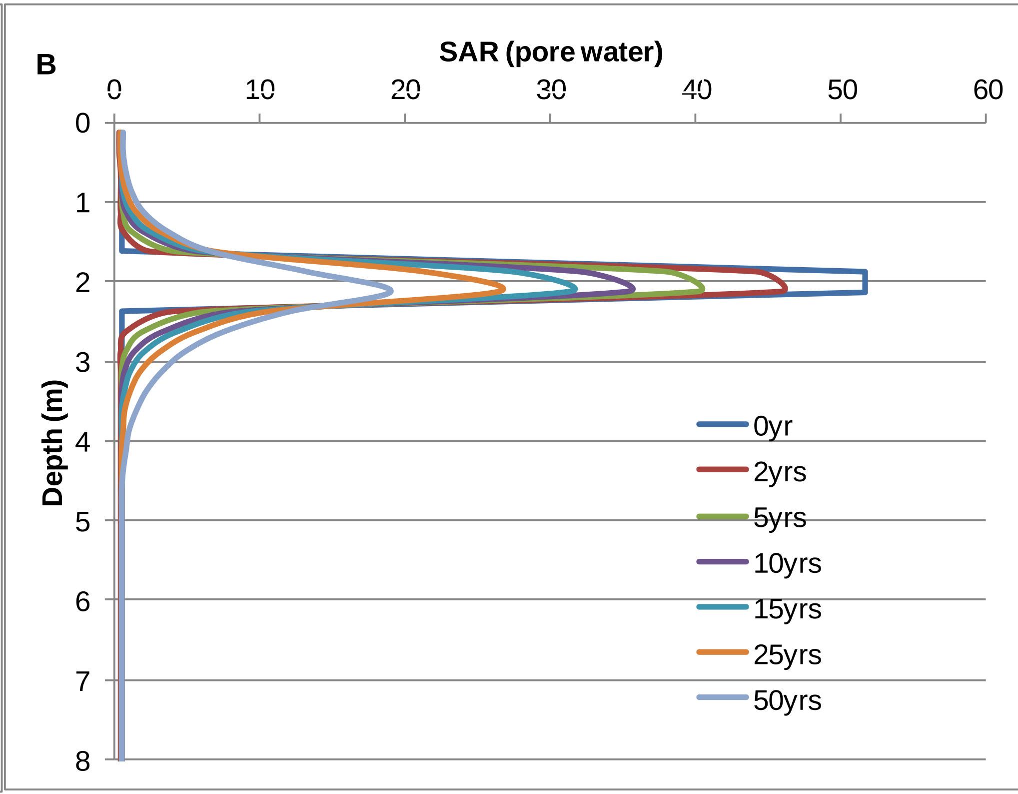
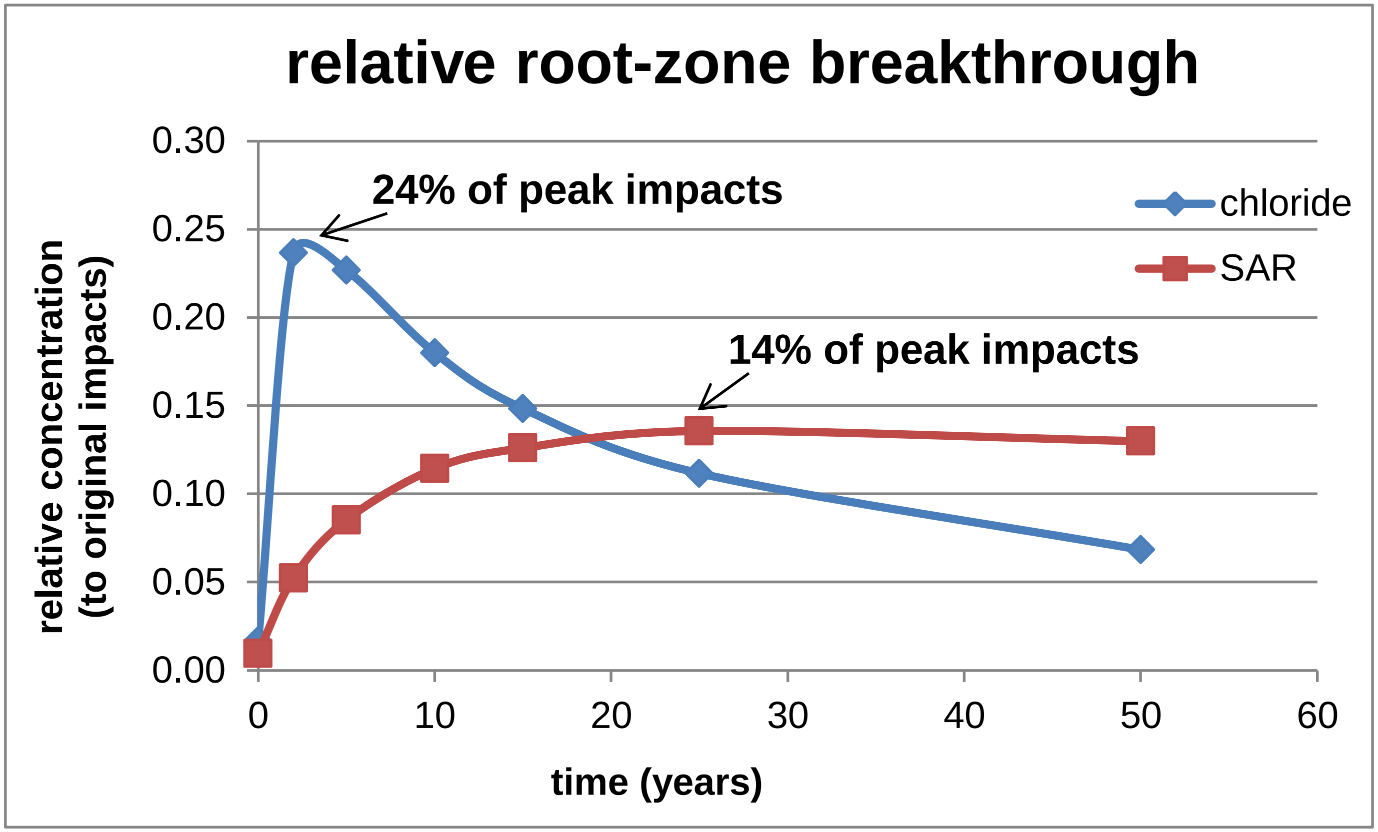


Figure 7.7. Modeling the magnitudes of peak SAR and chloride migration into root-zone



7.1.4 **Dugout pathway: Irrigation water**

The dugout scenario is a key SST risk pathway relevant to both livestock watering and irrigation. Though dugouts are intended to collect surface water from broad areas, there is some potential for impacted groundwater (if sufficiently shallow) to mix with this surface water and create potential risk. Irrigation water guidelines from SCARG are shown in Table 7.2 for both EC and SAR, with irrigation water considered ‘hazardous’ if above 2.5 dS/m or a SAR of 9. Within the existing SST version for subsoil chloride, this pathway is screened (and potentially excluded) by comparing background TDS in shallow groundwater to thresholds in this table. For example, if background EC in groundwater exceeds 2.5 dS/m (or approximately 1,600 mg/L TDS), the pathway may be ruled out due to high background salinity (and thus potentially hazardous background irrigation water). ‘Buffers’ for irrigation water are then calculated by comparing background salinity to the relevant threshold (either 1 or 2.5 dS/m depending on background salinity), and allowable concentrations of chloride which will not exceed this buffer are calculated during guideline derivation. For chloride, this guideline derivation includes either a 3-fold or 10-fold adjustment factor for mixing of groundwater with surface water depending on whether the soil is coarse-grained or fine-grained, respectively.

Table 7.2. Irrigation water guidelines for EC and SAR (source: SCARG, 2001)

Irrigation Water Parameter	Safe (all conditions)	Possibly Safe	Hazardous
EC dS/m	<1	1 – 2.5	>2.5
SAR	<4	4 – 9	>9

A similar methodology as for chloride may be used for irrigation SAR guidelines, though with some potential adjustments to account for differences in transport properties. For example, these 10-fold or 3-fold adjustment factors apply to individual ions and not directly to SAR. For instance, diluting all ions by 10-fold (fine soils) would result in SAR being diluted by $\sqrt{10}$, or approximately 3.2-fold. Similarly, diluting all ions by 3-fold (coarse soils) would result SAR being reduced by approximately $\sqrt{3}$, or approximately 1.7-fold. For example, Figure 7.8 shows an initial pore water EC of 5 dS/m and SAR of 30 being 10-fold diluted (fine soils) to 0.5 dS/m and SAR of 9.5. Note that this calculation assumes that surface water has zero dissolved cations (EC=0), which is unlikely to be the case as discussed below.

Surface water entering a dugout likely has some dissolved ions due to dissolution of natural background salts and calcite (Alberta Agriculture states that surface runoff into a dugout may often be of relatively poor quality). This effect is fairly negligible for chloride/TDS, but has significant implications for SAR guidelines where ratios of calcium to sodium may change significantly at low concentrations. For example, if it is assumed that surface water entering a dugout is comparable to river water (EC~0.3 dS/m, Ca~36 mg/L, and SAR~0.3 as per SCARG), this small calcium concentration has some notable influence on calculated SAR values. The resulting modified dilution curve is shown in Figure 7.9, where the same 10-fold mixing with surface water results in an estimated dugout water EC of 0.8 dS/m and SAR of 4.1. This is much closer to the ‘safe’ category than when assuming no cations are present in the surface water (run-off) entering the dugout, and likely provides a more realistic estimate of risk.

Figure 7.8. EC/SAR dilution curve assuming absence of all cations in surface water

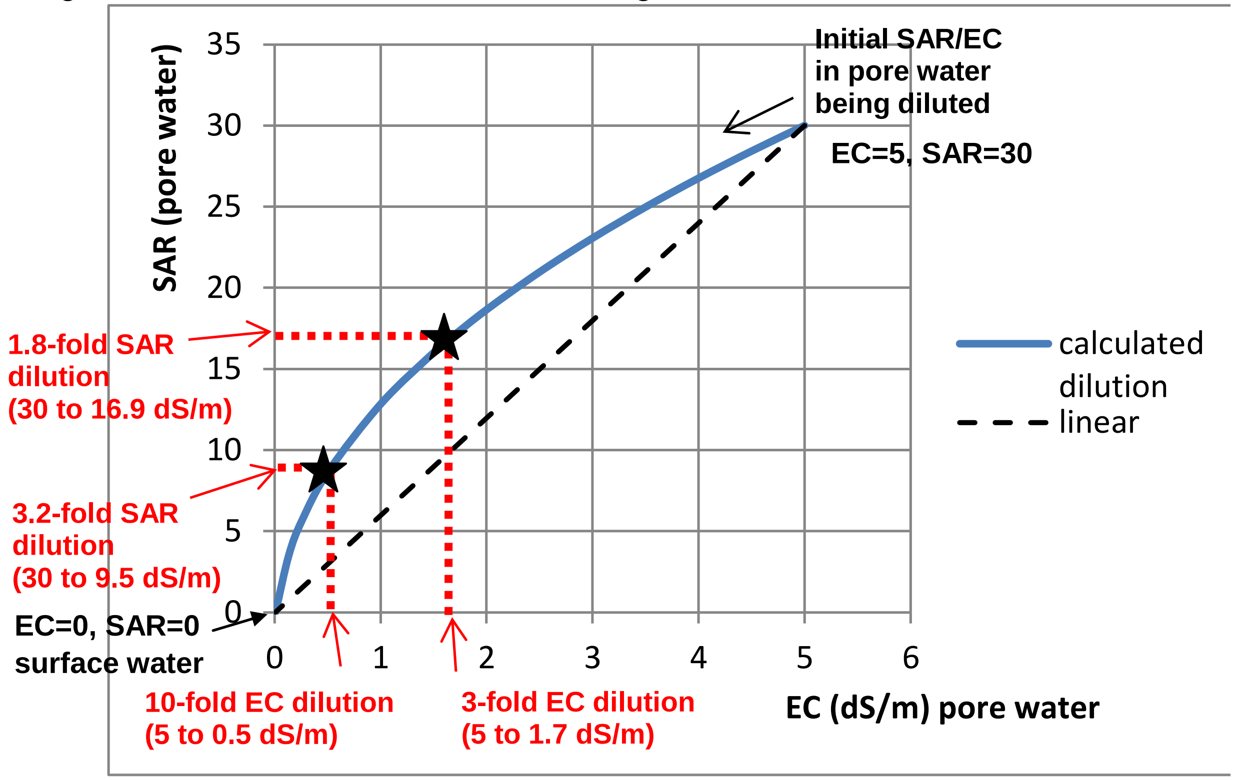
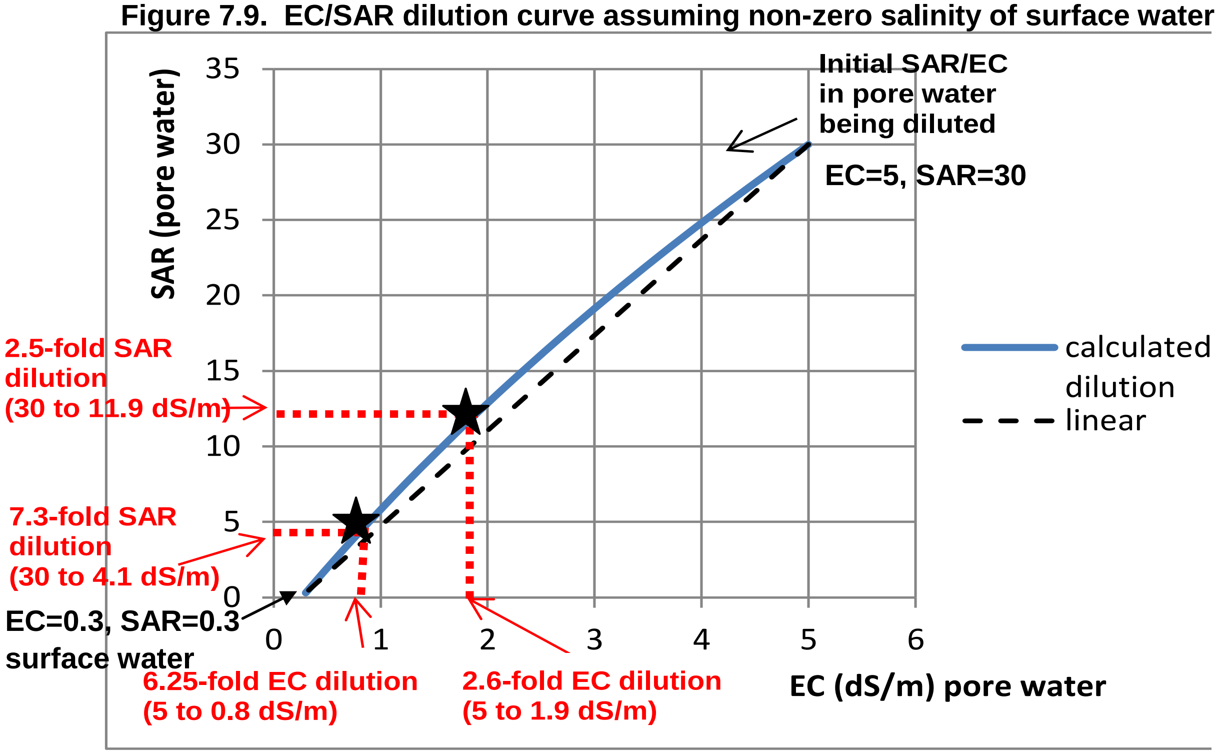


Figure 7.9. EC/SAR dilution curve assuming non-zero salinity of surface water



Regardless of the method used for the mixing calculation, there is also the policy issue regarding which dugout irrigation water guideline for SAR should be used for the irrigation water pathway. Table 7.2 showed irrigation SAR thresholds of <4 for ‘safe’, 4-9 for ‘possibly safe’. A SAR of >9 in irrigation water is considered hazardous and unusable. Current SST protocol selects a TDS category based on background TDS in shallow groundwater, and thus one approach could involve selecting different irrigation SAR guidelines based on site-specific factors such as background SAR or soil texture. For example, there could potentially be a distinction between fine and coarse soils since coarse soils are generally less sensitive to SAR.

7.1.5 **Dugout pathway: livestock water**

SAR and/or elevated sodium do not appear to pose any additional risk to livestock compared to the assumptions in the generic TDS guidelines for livestock watering. Thus, the existing SST protocol for chloride (which also assumes an appropriate balancing amount of sodium is also present) is also sufficiently protective of sodium in livestock water.

7.1.6 **DUA pathway**

Similar to the livestock water pathway, the existing SST protocol for chloride is sufficiently protective for sodium/SAR for the DUA pathway. The chloride guideline for drinking water (250 mg/L) is sufficiently protective since the drinking water guideline for sodium (200 mg/L) is higher (less constraining) than the stoichiometric amount of sodium which would be associated with 250 mg/L chloride assuming a sodium chloride source of impacts.

7.1.7 **Aquatic life pathway**

There is currently no freshwater aquatic life guideline for sodium, and thus it is judged that the chloride aquatic life guideline used in the SST (originally 230 mg/L, recently updated to 120 mg/L to be consistent with a CCME update) is sufficiently protective of sodium/SAR.

7.2 ADDITIONAL CONSIDERATIONS FOR SUBSOIL SAR GUIDELINES

Other auxiliary policy issues are also associated with the above SST pathways. One such issue is where there should there be a 'management limit' for subsoil SAR guidelines generated by the SST, or instead showing 'NGR' (no guideline required) for certain pathways if appropriate. This is highly relevant to low-risk scenarios such as deep, isolated SAR impacts where remediating to a potentially semi-arbitrary management limit may be un-necessary. For chloride, the SST currently has a management limit of 7,000 mg/kg chloride. A 'no guideline required' approach may be more suitable for certain pathways for these cases.

An additional issue is whether there should be any role for field observations for the presence or absence of water table ponding/perching/mounding. Monitoring well elevations (if available) and/or borehole logs may show anecdotal evidence or lack thereof of water table effects, and would be relevant to the soil structure/ponding pathway only. This type of anecdotal information has high amounts of uncertainty, and may therefore potentially only provide an indication of conditions during specific monitoring events and may miss potential future risk. Thus, this type of information may not be suitable to consider in the SST.

8 CONCLUSIONS AND NEXT STEPS

Previous and general conclusions from this research project include:

- The deleterious effects of SAR in soil have been studied for over 50 years, potentially causing losses in hydraulic conductivity due to swelling and dispersion of clay particles.

- The interactions between EC and SAR have also been studied for many years, with increased EC known to play a significant role in reducing the negative effects of SAR on soil dispersion. The majority of these studies are related to SAR in root-zone soils, often related to the application of sodic irrigation water.

- Subsoil SAR may pose less environmental risk than root-zone SAR due to the absence of exacerbating factors such as tillage, shear by rain drops, and dilution by low EC rainwater. Excess subsoil SAR may potentially cause water-logging or water-table perching which may indirectly affect plant growth if sufficiently close to the root-zone.

- Leaching columns are a useful technique for studying SAR effects, allowing the study of the interactions between SAR, EC, and K_{sat}. They also allow useful comparisons with previous leaching column work from literature.

- Water table modeling is a useful approach to evaluate the potential effects of reduced hydraulic conductivity (K_{sat}) on water transport and potential root-zone water-logging at a site. This water-table modeling can be performed on either a 1-dimensional or 3-dimensional basis, with 3-dimensional models allowing for improved realism and estimation of risk

- High SAR values may reduce K_{sat} by up to 1-3 orders of magnitude, with the largest effects typically occurring at lowest EC's. Some soils may be less sensitive to SAR than others, such as coarse soils or soils initially low in hydraulic conductivity

- Many SAR effects appear to be reversible, with calcium and magnesium salts effective in many cases for remediating SAR. Sufficiently high EC can also reverse SAR effects in many cases without the use of traditional calcium salts.

Updated conclusions from this 2011-2012 stage of the project include:

- Additional leaching column experiments have expanded the database of SAR/EC/Ksat interactions for a variety of textures and geographical regions. They have confirmed that coarse, sandy soils are typically less sensitive to SAR effects than finer soils with higher clay content, but with some noteworthy exceptions such high-clay content soils with low initial conductivity which also appear to be relatively insensitive to SAR. Soils with moderate values for initial hydraulic conductivity may thus have the potential to be most sensitive to SAR-induced K_{sat} losses.

- Organic soils such as peats appear to be highly insensitive to SAR, and thus likely require separate consideration compared to typical mineral soils

- A synthesis of leaching column experiments to-date suggests that undisturbed field cores have generally comparable behaviour to repacked soils from literature, though the undisturbed field cores may have an increased range of potential SAR responses compared to homogenized repacked cores from literature. This is potentially due to factors such as variations in soil layering, macro-pores, compaction (bulk density), and other factors. Since these undisturbed cores are highly relevant to practical field conditions, this suggests that two soils with similar texture may display different responses to changes in SAR based on initial hydraulic conductivity, bulk density, or other factors. Some undisturbed field soils may thus be more sensitive than average (and potentially more sensitive than literature curves), and thus some type of statistical consideration of the range of soil responses may be appropriate when generating SAR/EC/K_{sat} thresholds. Collection of additional soil data such as bulk density (in addition to texture) may help refine the predictions of the potential response of field soils to SAR.

- Expanded water-table modeling suggests that K_{sat} losses of up to 10-fold or more may be tolerated in a large number of scenarios without likely causing a water-logged zone. This is comparable to typical natural variability observed in non-SAR impacted soils within similar soil textures

- The future leaching of EC out of soils often occurs faster than SAR depending on background conditions and the magnitude of the EC/SAR impacts. Empirically, these appear to follow a similar general EC/SAR trajectory as the thresholds they are being compared to when at low values of EC

- An SST-like framework is one promising possibility for implementing subsoil SAR guidelines providing an improved ability to manage subsoil SAR impacts more effectively. Such a framework could provide the ability to generate subsoil SAR guidelines which would be unlikely to cause potential root-zone SAR exceedances or water-logging in future. It also provides a mechanism to evaluate other SST pathways such as dugouts.

- Upward migration of sodium into the root-zone is a complex process with numerous factors such as cation exchange capacity and the EC and SAR of the root-zone material playing a significant role in the potential for future root-zone SAR increases.

- The dugout pathway may pose a risk to soil structure if SAR-impacted soils result in unacceptably high irrigation water SAR after mixing with surface water in a dugout. These risk calculations are influenced by which irrigation threshold is being compared against, and whether the surface water is considered to be completely cation-free or containing some realistic estimate of dissolved background salts/cations.

- There is no SAR guideline for drinking water, and the DUA pathway is likely sufficiently protected by chloride guidelines since the drinking water for sodium is relatively less constraining than the drinking water guideline for chloride.

Recommended next steps for subsoil SAR guideline development include additional discussions through the PTAC Salinity Working Group to refine various policy and regulatory issues surrounding the implementation of subsoil SAR guidelines in the Subsoil Salinity Tool (SST). This may involve additional algorithm refinement and/or transport modeling depending on the key issues identified and implementation methods chosen.

9 CLOSURE

This document was prepared by Equilibrium Environmental Inc. under contract to Environment Canada solely for the purpose of providing information relevant to the development of subsoil salinity guidelines. Equilibrium does not accept responsibility for the use of this report for any purpose other than intended or to any third party unless otherwise stated, in whole or in part, and we exercise no duty of care in relation to this report to any third party. Any questions regarding this document should be direct to Greg Huber or Anthony Knafla at (403) 286 7706.

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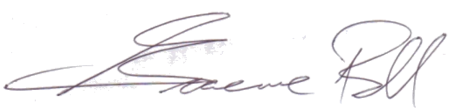

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