IRRIGATION WATER QUALITY FOR AGRICULTURE

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Irrigation Water Background

In the past, there were minor concerns for farmers or agricultural crop advisors regarding either the quantity or the quality of irrigation water in Georgia. This is because only a small amount of acreage under irrigated agriculture utilized potable (suitable for drinking) quality water. Thus, quality of irrigation water was not closely monitored or regulated. However, recently the nature and extent of irrigated agriculture has changed with respect to water quantity and quality in Georgia as well as in several other states. With growing demands for potable water (due to population increase) and expanding irrigated acreage, there is an increased pressure on irrigated farms to consider using non-potable alternatives.

Figure 1. Changes in irrigated acreage in Georgia during 1970-2008 (Source: State Water Plan 2008, available at www.georgiawaterplanning.org). *Note: No data on the irrigated acreages of various crops are available for the years after 2008 because no irrigation survey was conducted after 2008.*

According to the Georgia Comprehensive State-wide Water Management Plan (State Water Plan) 2008 (available at www.georgiawaterplanning.org), the irrigated acreage in Georgia increased from 0.2 million acres in 1975 to around 1.5 million acres in 2008 (Figure 1). A progressive increase in irrigated acreage has been forecasted in years to come, surpassing 1.65 million acres in 2050.
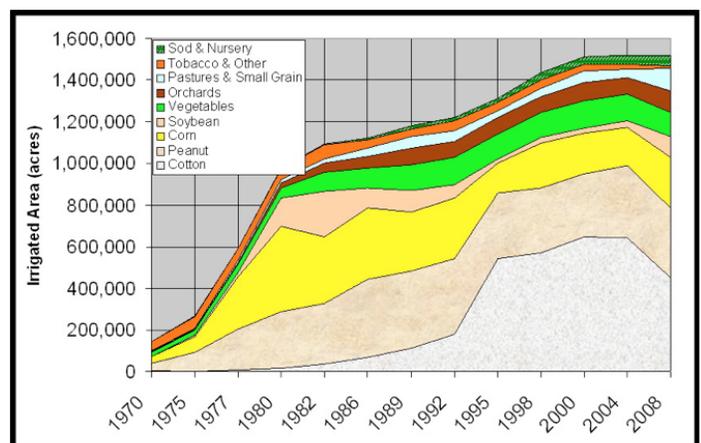
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Historically, traditional row crops such as cotton, peanut, corn, and soybean dominate the Georgia agricultural landscape. Additionally, pecans, vegetables and fruit, nurseries and other specialty crops are economically significant and account for a large share of irrigation water use.

Why Does Irrigation Water Quality Matter?

Understanding irrigation water quality is critical to determining appropriate crop and soil management practices that are necessary for long-term productivity. Water quality affects:

- Fertility needs of the crop
- Crop yield
- Soil physical conditions
- Soil salinity
- Irrigation system performance and longevity
- Water application method

What Are the Major Attributes of Irrigation Water Quality?

Typically, qualities of irrigation water deserving primary consideration include:

- Soluble salts content
- Sodium concentration
- Concentration of toxic elements and compounds
- Presence and abundance of macro- and micro-nutrients, and trace elements
- Alkalinity, acidity, and hardness of the water

Know Your Water Quality!

- Quality of water for agricultural irrigation is critical to understanding management for long-term productivity.

- In some cases, irrigation water quality can be a more important factor influencing crop yield than soil fertility, cultivar used, weed control, and other factors.

- Low quality irrigation water can adversely affect soil physical conditions.

Depending on the circumstances, the suspended sediment concentration, bacterial content, and temperature of irrigation water may also deserve attention.

Common Units Used to Express and Evaluate Irrigation Water Quality

Water quality parameters are reported in various units depending on the laboratory. An understanding of these units and the conversion factors to convert one to another could be helpful. Use Table 1 for this purpose.

Table 1. Useful conversion factors for understanding irrigation water quality analysis reports (Adapted from Bauder et al., 2007).

Component	Convert From	Multiply By	Convert To
Water nutrient or TDS[1]	mg/L	1.0	ppm
Water nutrient or TDS	mg/L or ppm	0.227	lb/acre-inch of water
Water salinity (EC_w)[2]	dS/m	1.0	mmohs/cm
Water salinity (EC_w)	mmhos/cm	1000	µmhos/cm
Water salinity (EC_w)	dS/m	1000	µmhos/cm
Water salinity (EC_w)	For EC_w lower than 5 dS/m	640	TDS in mg/L or ppm
Water salinity (EC_w)	For EC_w higher than 5 dS/m	800	TDS in mg/L or ppm
Calcium content of water	mg/L or ppm	0.0499	meq/L
Magnesium content of water	mg/L or ppm	0.0823	meq/L
Sodium content of water	mg/L or ppm	0.0435	meq/L
Carbonate content of water	mg/L or ppm	0.0167	meq/L
Bicarbonate content of water	mg/L or ppm	0.0163	meq/L
Chloride content of water	mg/L or ppm	0.0282	meq/L
Water NO_3-N, SO_4-S, B applied	mg/L or ppm	2.72	lb/acre-foot of water
Water NO_3-N, SO_4-S, B applied	mg/L or ppm	0.227	lb/acre-inch of water
Irrigation water	acre-inch	27,150	gallons of water

[1] TDS means total dissolved solids in the irrigation water; ppm stands for "parts per million."

[2] EC_w means electrical conductivity of the irrigation water.

Soluble Salts Content or Salinity or Conductivity

All water contains some salts [*Note: Salts for the purpose of irrigation water quality include not only sodium chloride (common/table salt), but also other chorides, carbonate/bicarbonates, and sulfate salts of sodium, calcium, and magnesium*]. Typically, groundwater contains more salts than surface water. Water salinity represents the amount of dissolved salts in water. It is usually measured by the ability of water to conduct electricity, called "Electrical Conductivity" or EC. The EC of water (EC_w) goes up with the increase of dissolved salts. The EC_w is reported in one of the three acceptable units: deciSiemen per meter (dS/m), millimhos per centimeter (mmhos/cm), or micromhos per centimeter (µmhos/cm). The conversion factors for one unit to another are given below:

- 1 dS/m = 1 mmho/cm = 1,000 µmhos/cm

Another measure of water salinity is Total Dissolved Solids (TDS). It is sometimes referred to as the total salinity and is expressed in parts per million (ppm), which is equivalent to another unit called milligrams per liter (mg/L). Another important unit used in water salinity analysis and management is millequivalent per liter (meq/L); the factor to convert mg/L to meq/L and vice versa depends on the element or compound in question (Table 1).

A "Rough" Estimate of Salt in Water

Water with electrical conductivity (EC_w) of only 1.15 dS/m contains approximately 2,000 pounds of salt for every acre-foot of water.

Harmful Effects of Soluble Salts Content or Salinity of Irrigation Water

Water with high salinity that is harmful to plants is called a *salinity hazard*. High concentrations of salts in the soil's water (soil solution) can result in a physiological drought condition in field crops. Under such conditions, a crop may appear stressed for water and even wilt despite the availability of adequate soil moisture because the roots are not able to absorb the water from a concentrated soil solution.

A number of useful guidelines for evaluating salinity hazard of irrigation water are available. A brief summary of those guidelines is presented in Table 2. *Note: hazards from irrigation water salinity and soil salinity are not equivalent.*

Tolerance of various crops to the salinity of irrigation water is given in Tables 3a-d. They may be used as a guideline for selecting crops based on the available irrigation water salinity.

Table 2. A brief guideline for the assessment of salinity hazard of irrigation water (Adapted from Ayres and Wescot, 1985; Western Fertilizer Handbook, 1995).

Measures of Salinity	Degree of Restriction on Use		
	None	**Slight to Moderate**	**Severe**
EC_w[1] (mmhos/cm or dS/m)	< 0.7	0.7–3.0	> 3.0
TDS[1] (mg/L)	< 450	450–2,000	> 2,000

Table 3a. Yield potential and irrigation water salinity tolerance of field crops (Adapted from Ayres and Westcot, 1985; Fipps, 2003).

Field Crop	Expected Yield Reduction in Percent at various EC_w				Maximum Tolerable EC_w (mmohs/cm or dS/m)[2]
	0%	**10%**	**25%**	**50%**	
	EC_w (mmohs/cm or dS/m)[1]				
Barley (*Hordeum vulgare*)[3]	5.3	6.7	8.7	12	19
Broadbean (*Vicia faba*)	1.1	1.8	2.0	4.5	8.0
Bean (*Phaseolus vulgaris*)	0.7	1.0	1.5	2.4	4.2
Corn (*Zea mays*)	1.1	1.7	2.5	3.9	6.7
Cotton (*Gossypium hirsutum*)	5.1	6.4	8.4	12	18
Cowpea (*Vigna unguiculata*)	3.3	3.8	4.7	6.0	8.8
Flax (*Linum usitatissimum*)	1.1	1.7	2.5	3.9	6.7
Groundnut (peanut) (*Arachis hypogaea*)	2.1	2.4	2.7	3.3	4.4
Rice (paddy) (*Oriza sativa*)	2.0	2.6	3.4	4.8	7.6
Sorghum (*Sorghum bicolor*)	4.5	5.0	5.6	6.7	8.7
Soybean (*Glycine max*)	3.3	3.7	4.2	5.0	6.7
Sugarbeet (*Beta vulgaris*)[4]	4.7	5.8	7.5	10	16
Wheat (*Triticum aestivum*)[3, 5]	4.0	4.9	6.3	8.7	13
Wheat, durum (*Triticum turgidum*)	3.8	5.0	6.9	10	16

[1] EC_w means electrical conductivity of the irrigation water in mmohs/cm of deciSiemens per meter (dS/m).

[2] The maximum tolerable EC_w indicates the theoretical irrigation water salinity at which crop growth ceases.

[3] Barley and wheat are less tolerant during germination and seeding stage.

[4] Beets are more sensitive during germination.

[5] Semi-dwarf, short cultivars may be less tolerant.

Table 3b. Yield potential and irrigation water salinity tolerance of vegetable crops (Adapted from Ayres and Westcot, 1985; Fipps, 2003).

Vegetable Crop	Expected Yield Reduction in Percent at various EC_w				Maximum Tolerable EC_w (mmohs/cm or dS/m)[2]
	0%	10%	25%	50%	
	EC_w (mmohs/cm or dS/m)[1]				
Bean (*Phaseolus vulgaris*)	0.7	1.0	1.5	2.4	4.2
Beet, red (*Beta vulgaris*)[3]	2.7	3.4	4.5	6.4	10
Broccoli (*Brassica oleracea botrytis*)	1.9	2.6	3.7	5.5	9.1
Cabbage (*Brassica oleracea capitata*)	1.2	1.9	2.9	4.6	8.1
Carrot (*Daucus carota*)	0.7	1.1	1.9	3.0	5.4
Celery (*Apium graveolens*)	1.2	2.3	3.9	6.6	12
Corn, sweet (*Zea mays*)	1.1	1.7	2.5	3.9	6.7
Cucumber (*Cucumis sativus*)	1.7	2.2	2.9	4.2	6.8
Lettuce (*Lactuca sativa*)	0.9	1.4	2.1	3.4	6.0
Onion (*Allium cepa*)	0.8	1.2	1.8	2.9	5.0
Pepper (*Capsicum annuum*)	1.0	1.5	2.2	3.4	5.8
Potato (*Solanum tuberosum*)	1.1	1.7	2.5	3.9	6.7
Radish (*Raphanus sativus*)	0.8	1.3	2.1	3.4	5.9
Spinach (*Spinacia oleracea*)	1.3	2.2	3.5	5.7	10
Squash, scallop (*Cucurbita pepo melopepo*)	2.1	2.6	3.2	4.2	6.3
Squash, zucchini (courgette) (*Cucurbita pepo melopepo*)	3.1	3.8	4.9	6.7	10
Sweet potato (*Ipomoea batatas*)	1.0	1.6	2.5	4.0	7.1
Tomato (*Lycopersicon esculentum*)	1.7	2.3	3.4	5.0	8.4
Turnip (*Brassica rapa*)	0.6	1.3	2.5	4.3	8.0

[1] EC_w means electrical conductivity of the irrigation water in mmohs/cm of deciSiemens per meter (dS/m).

[2] The maximum tolerable EC_w indicates the theoretical irrigation water salinity at which crop growth ceases.

[3] Beets are more sensitive during germination.

Table 3c. Yield potential and irrigation water salinity tolerance of forage crops (Adapted from Ayres and Westcot, 1985; Fipps, 2003).

| Forage Crop | Expected Yield Reduction in Percent at various EC_w | | | | Maximum Tolerable EC_w (mmohs/cm or dS/m)[2] |
| | 0% | 10% | 25% | 50% | |
	EC_w (mmohs/cm or dS/m)[1]				
Alfalfa (*Medicago sativa*)	1.3	2.2	3.6	5.9	10
Barley (forage) (*Hordeum vulgare*)[3]	4.0	4.9	6.4	8.7	13
Bermuda grass (*Cynodon dactylon*)[4]	4.6	5.6	7.2	9.8	15
Clover (*Trifolium alexandrinum*)	1.0	2.2	3.9	6.8	13
Clover, red (*Trifolium pratense*)	1.0	1.6	2.4	3.8	6.6
Clover, alsike (*Trifolium hybridum*)	1.0	1.6	2.4	3.8	6.6
Clover, ladino (*Trifolium repens*)	1.0	1.6	2.4	3.8	6.6
Clover, strawberry (*Trifolium fragiferum*)	1.0	1.6	2.4	3.8	6.6
Corn (forage) (*Zea mays*)	1.2	2.1	3.5	5.7	10
Cowpea (forage) (*Vigna unguiculata*)	1.7	2.3	3.2	4.8	7.8
Foxtail, meadow (*Alopecurus pratensis*)					
Harding grass (*Phalaris tuberosa*)	3.1	3.9	5.3	7.4	12
Orchard grass (*Dactylis glomerata*)	1.0	2.1	3.7	6.4	12
Lovegrass (*Eragrostis* sp.)	1.3	2.1	3.3	5.3	9.3
Perennial ryegrass (*Lolium perenne*)	3.7	4.6	5.9	8.1	13
Sesbania (*Sesbania exaltata*)	1.5	2.5	3.9	6.3	11
Sudan grass (*Sorghum sudanense*)	1.9	3.4	5.7	9.6	17
Tall fescue (*Festuca elatior*)	2.6	3.6	5.2	7.8	13
Wheatgrass, tall (*Agropyron elongatum*)	5.0	6.6	9.0	13	21
Wheatgrass, crested (*Agropyron cristatum*)	5.0	6.0	7.4	9.8	15
Wheatgrass, siberian (*Agropyron sibiricum*)	2.3	4.0	6.5	11	19
Wildrye, beardless (*Elymus triticoides*)	1.8	2.9	4.6	7.4	13
Vetch, common (*Vicia angustifolia*)	2.0	2.6	3.5	5.0	8.1

[1] EC_w means electrical conductivity of the irrigation water in mmohs/cm of deciSiemens per meter (dS/m).

[2] The maximum tolerable EC_w indicates the theoretical irrigation water salinity at which crop growth ceases.

[3] Barley and wheat are less tolerant during germination and seeding stage.

[4] Tolerance given is an average of several varieties; Suwannee and Coastal Bermuda grass are about 20 percent more tolerant, while Common and Greenfield Bermuda grass are about 20 percent less tolerant.

Table 3d. Yield potential and irrigation water salinity tolerance of fruit crops (Adapted from Ayres and Westcot, 1985; Fipps, 2003).

| Fruit Crop | Expected Yield Reduction in Percent at various EC_W | | | | Maximum Tolerable EC_W (mmohs/cm or dS/m)[2] |
| | 0% | 10% | 25% | 50% | |
	EC_W (mmohs/cm or dS/m)[1]				
Almond (*Prunus dulcis*)[3]	1.0	1.4	1.9	2.8	4.5
Apple, pear (*Malus domestica, Pyrus* sp.)	1.0	1.6	2.2	3.2	-
Apricot (*Prunus armeniaca*)[3]	1.1	1.3	1.8	2.5	3.8
Avocado (*Persea americana*)	0.9	1.2	1.7	2.4	-
Blackberry (*Rubus* sp.)	1.0	1.3	1.8	2.5	4.0
Boysenberry (*Rubus ursinus*)	1.0	1.3	1.8	2.5	4.0
Date palm (*phoenix dactylifera*)	2.7	4.5	7.3	12	21
Fig, olive, pomegranate (*Ficus carica, Olea sp., Punica granatum*)	1.8	2.6	3.7	5.6	-
Grape (*Vitus* sp.)[3]	1.0	1.7	2.7	4.5	7.9
Grapefruit (*Citrus paradisi*)[3]	1.2	1.6	2.2	3.3	5.4
Lemon, lime (*Citrus* sp.)	1.6	1.6	2.2	3.2	-
Orange (*Citrus sinensis*)	1.1	1.6	2.2	3.2	5.3
Peach (*Prunus persica*)	1.1	1.5	1.9	2.7	4.3
Plum, prune (*Prunus domestica*)[3]	1.0	1.4	1.9	2.9	4.7
Strawberry (*Fragaria* sp.)	0.7	0.9	1.2	1.7	2.7
Walnut (*Juglans regia*)	1.1	1.6	2.2	3.2	-

[1] EC_W means electrical conductivity of the irrigation water in mmohs/cm of deciSiemens per meter (dS/m).
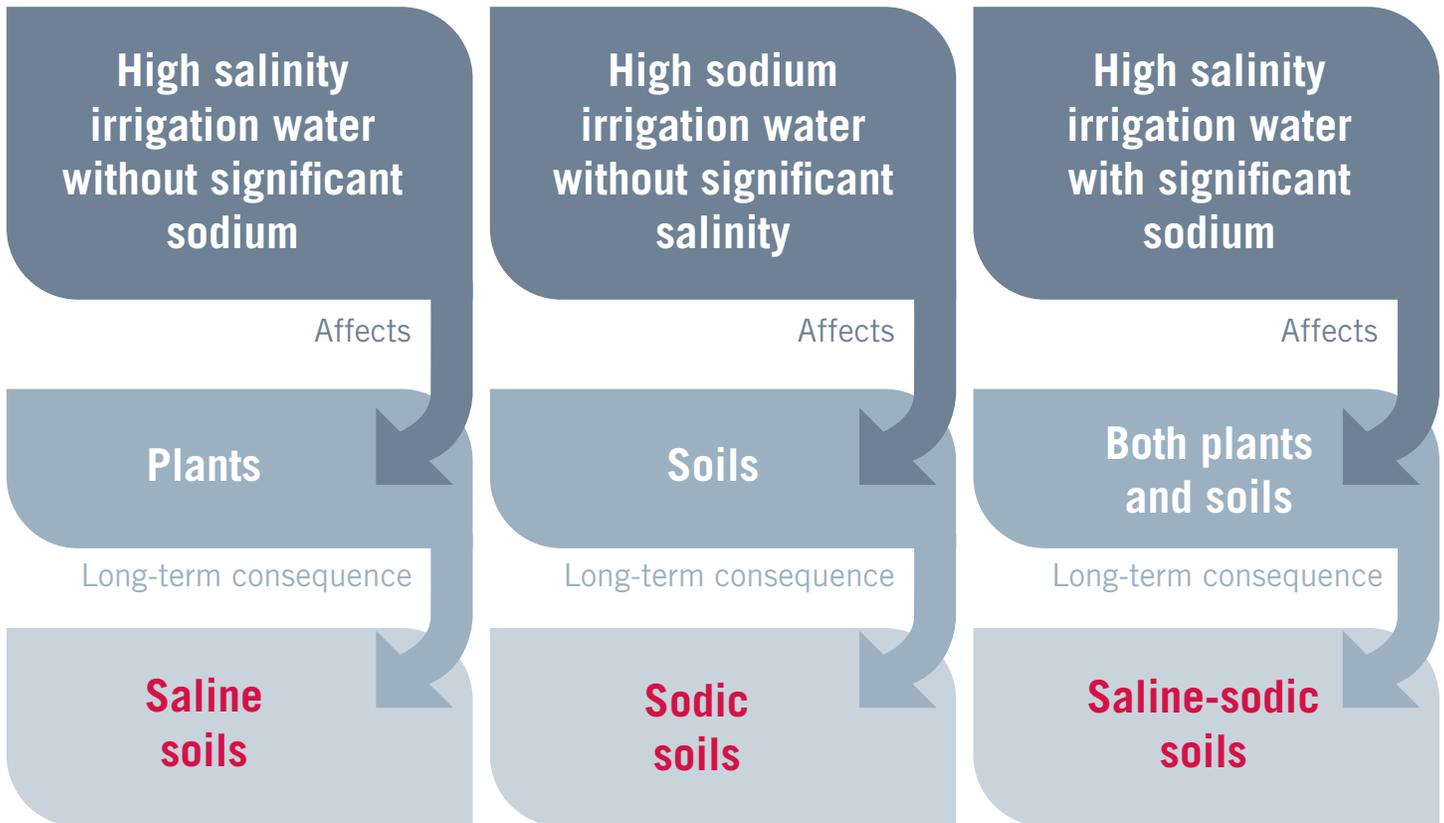
[2] The maximum tolerable EC_W indicates the theoretical irrigation water salinity at which crop growth ceases.

[3] Tolerance evaluation is based on tree growth and not on yield.

Water salinity can also adversely affect soil properties. Depending on the type of salts present, long-term use of high salinity irrigation water results in soils with high levels of salts, sodium, or salts + sodium referred to as *saline soils, sodic soils,* or *saline-sodic soils,* respectively. In general, these soils are called salt-affected soils. Growing crops on salt-affected soils requires special cultural management.

Usefulness of Soil and Water Salinity Information

Knowledge of both soil and water salinity and correspondingly appropriate management strategies are required in order to avoid a risk of reduction in long-term crop productivity.

High salinity irrigation water without significant sodium	High sodium irrigation water without significant salinity	High salinity irrigation water with significant sodium
Affects	Affects	Affects
Plants	Soils	Both plants and soils
Long-term consequence	Long-term consequence	Long-term consequence
Saline soils	Sodic soils	Saline-sodic soils

Presence of Sodium Versus Calcium and Magnesium Salts

The relative proportion of sodium (Na) to calcium (Ca) and magnesium (Mg) in irrigation water is another important aspect of evaluating its quality, often called sodicity of irrigation water. Relatively high sodium and low calcium and magnesium content are of special concern due to sodium's adverse effects on the soil. Continued use of irrigation water with sodium in excess of calcium and magnesium leads to a very tight soil structure with poor water infiltration, poor aeration, and increased surface crusting; these conditions make tillage difficult and restrict seedling emergence and root growth, called *sodium hazard*. Calcium and magnesium tend to counter the adverse effects of sodium and promote good soil aggregates.

Sodium Hazard Varies With Soil Texture

Fine textured soils, especially those high in clay (smectite clay in particular), are most vulnerable to sodium hazard.

Potential *sodium hazard* from irrigation water is usually evaluated by an index called *sodium adsorption ratio* or SAR. The SAR is calculated from the ratio of the concentration of sodium to that of calcium and magnesium (Equation 1).

Equation 1:

$$SAR = \frac{[Na^+]}{\sqrt{\frac{1}{2}([Ca^{2+}] + [Mg^{2+}])}}$$

The concentrations of sodium, calcium, and magnesium ($[Na^+]$, $[Ca^{2+}]$, and $[Mg^{2+}]$) in Equation 1 are in milliequivalents per liter (meq/L). The conversion factors for the concentrations expressed in mg/L or ppm to meq/L are given below:

1 mg/L or 1 ppm Na = 0.0435 meq/L $[Na^+]$

1 mg/L or 1 ppm Ca = 0.0499 meq/L $[Ca^{2+}]$

1 mg/L or 1 ppm Mg = 0.0823 meq/L $[Mg^{2+}]$

Bicarbonate and carbonate ions in the irrigation water increases the sodium hazard as quantified by SAR described above. This occurs because bicarbonate and carbonate ions can bind some calcium and magnesium, thereby reducing their availability to counteract the hazardous effects of sodium.

Use of Adjusted-SAR (adjR$_{Na}$)

For irrigation waters containing significant amounts of bicarbonate and carbonate, the adjusted-SAR (adjR$_{Na}$) should be used (instead of SAR) should be used to evaluate the potential sodium hazard.

In calculating adjusted-SAR (adjR$_{Na}$), an adjusted calcium concentration ($[Ca_x^{2+}]$) is estimated using the bicarbonate + carbonate concentration and EC of the irrigation water. Then adjR$_{Na}$ is calculated as shown in Equation 2.

Equation 2:

$$\mathbf{adjR_{Na}} = \frac{[Na^+]}{\sqrt{\frac{1}{2}([Ca_x^{2+}] + [Mg^{2+}])}}$$

The adjR$_{Na}$ is a truer index of water sodicity and the risk of sodium hazard on soil properties. Because in irrigation water with significant bicarbonate + carbonate concentration, the adjusted calcium concentration ($[Ca_x^{2+}]$) is lower than the actual calcium concentration and the adjR$_{Na}$ is greater than the SAR. Most adjR$_{Na}$ values of irrigation waters are about 10 to 15 percent greater than the unadjusted SAR.

Calculation of Adjusted Sodium Adsorption Ratio (adjR$_{Na}$)

The adjusted calcium concentration ($[Ca_x^{2+}]$) is estimated using the following procedure:

1. Calculate the sum of bicarbonate $[HCO_3^-]$ and carbonate $[CO_3^{2-}]$ in meq/L and consider that as just bicarbonate $[HCO_3^-]$ for this calculation purpose.

2. Calculate the ratio of $[HCO_3^-]$ / Calcium $[Ca^{2+}]$ in meq/L.

3. On the left side of **Table 4**, find the ratio nearest to the calculated $[HCO_3^-]$ / Calcium $[Ca^{2+}]$ ratio.

4. Along the top of **Table 4**, find the EC$_w$ nearest to the measured EC$_w$.

5. Move down the column of numbers corresponding to the EC$_w$ value until the row of numbers corresponding to the ratio is reached.

6. The number at the intersection of the column and the row is the adjusted calcium concentration ($[Ca_x^{2+}]$).

7. Use this adjusted calcium concentration ($[Ca_x^{2+}]$) to calculate the adjusted-SAR (adjR$_{Na}$) using **Equation 2**.

Table 4. Adjusted calcium concentration ($[Ca_x^{2+}]$) for irrigation water with various $[HCO_3^-]$ / Calcium $[Ca^{2+}]$ ratios and salinity (EC$_w$) levels (Adapted from Ayres and Westcot, 1985).

Ratio of Bicarbonate $[HCO_3^-]$ / Calcium $[Ca^{2+}]$	Salinity of Irrigation Water (dS/m or mmhos/cm)											
	0.1	0.2	0.3	0.5	0.7	1.0	1.5	2.0	3.0	4.0	6.0	8.0
0.05	13.20	13.61	13.92	14.40	14.79	15.26	15.91	16.43	17.28	17.97	19.07	19.94
0.10	8.31	8.57	8.77	9.07	9.31	9.62	10.02	10.35	10.89	11.32	12.01	12.56
0.15	6.34	6.54	6.69	6.92	7.11	7.34	7.65	7.90	8.31	8.64	9.17	9.58
0.20	5.24	5.40	5.52	5.71	5.87	6.06	6.31	6.52	6.86	7.13	7.57	7.91
0.25	4.51	4.65	4.76	4.92	5.06	5.22	5.44	5.62	5.91	6.15	6.52	6.82
0.30	4.00	4.12	4.21	4.36	4.48	4.62	4.82	4.98	5.24	5.44	5.77	6.04
0.35	3.61	3.72	3.80	3.94	4.04	4.17	4.35	4.49	4.72	4.91	5.21	5.45
0.40	3.30	3.40	3.48	3.60	3.70	3.82	3.98	4.11	4.32	4.49	4.77	4.98
0.45	3.05	3.14	3.22	3.33	3.42	3.53	3.68	3.80	4.00	4.15	4.41	4.61
0.50	2.84	2.93	3.00	3.10	3.19	3.29	3.43	3.54	3.72	3.87	4.11	4.30
0.75	2.17	2.24	2.29	2.37	2.43	2.51	2.62	2.70	2.84	2.95	3.14	3.28
1.00	1.79	1.85	1.89	1.96	2.01	2.09	2.16	2.23	2.35	2.44	2.59	2.71
1.25	1.54	1.59	1.63	1.68	1.73	1.78	1.86	1.92	2.02	2.10	2.23	2.33
1.50	1.37	1.41	1.44	1.49	1.53	1.58	1.65	1.70	1.79	1.86	1.97	2.07
1.75	1.23	1.27	1.30	1.35	1.38	1.43	1.49	1.54	1.62	1.68	1.78	1.86
2.00	1.13	1.16	1.19	1.23	1.26	1.31	1.36	1.40	1.48	1.54	1.63	1.70
2.25	1.04	1.08	1.10	1.14	1.17	1.21	1.26	1.30	1.37	1.42	1.51	1.58
2.50	0.97	1.00	1.02	1.06	1.09	1.12	1.17	1.21	1.27	1.32	1.40	1.47
3.00	0.85	0.89	0.91	0.94	0.96	1.00	1.04	1.07	1.13	1.17	1.24	1.30
3.50	0.78	0.80	0.82	0.85	0.87	0.90	0.94	0.97	1.02	1.06	1.12	1.17
4.00	0.71	0.73	0.75	0.78	0.80	0.82	0.86	0.88	0.93	0.97	1.03	1.07
4.50	0.66	0.68	0.69	0.72	0.74	0.76	0.79	0.82	0.86	0.90	0.95	0.99
5.00	0.61	0.63	0.65	0.67	0.69	0.71	0.74	0.76	0.80	0.83	0.88	0.93
7.00	0.49	0.50	0.52	0.53	0.55	0.57	0.59	0.61	0.64	0.67	0.71	0.74
10.0	0.39	0.40	0.41	0.42	0.43	0.45	0.47	0.48	0.51	0.53	0.56	0.58
20.0	0.24	0.25	0.26	0.26	0.27	0.28	0.29	0.30	0.32	0.33	0.35	0.37
30.0	0.18	0.19	0.20	0.20	0.21	0.21	0.22	0.23	0.24	0.25	0.27	0.28

Calculation Example

Go through the chemical analyses, the calculated SAR and the adjusted-SAR (adjR$_{Na}$) of two irrigation waters in Table 5, and the calculation details underneath Table 5.

Table 5. The unadjusted and adjusted SAR values of two irrigation waters for calculation example.

Irrigation Water	Concentration (meq/L)					EC (mmhos/cm)	[Ca$_x$$^{2+}$] (meq/L)	Calculated*	
	Ca	Mg	Na	Carbonate	Bicarbonate			SAR	adjR$_{Na}$
Water 1	2.32	1.44	7.73	0.42	3.66	1.15	1.43	5.64	6.45
Water 2	0.93	0.50	11.75	0.88	5.65	1.50	0.59	13.90	15.92

*Note: SAR=Unadjusted SAR; adjR$_{Na}$=Adjusted SAR.

Calculation Details

- *Water 1*

    a. **SAR** = 7.73 / ((1.44 + 2.32) / 2)$^{1/2}$ = 7.73 / 1.37 = 5.64.

    b. Adjusted-SAR (***adjR$_{Na}$***).

    l. Sum of [HCO$_3$$^-$] + [CO$_3$$^{2-}$] = 3.66 + 0.42 = 4.08.

    2. [HCO$_3$$^-$] / [Ca^{2+}] = 4.08 / 2.32 = 1.758.

    3. From **Table 4**, for an EC of about 1.0 dS/m and a [HCO$_3$$^-$] / [Ca^{2+}] ratio of about 1.75, the [Ca$_x$$^{2+}$] is 1.43 meq/L.

    4. Therefore, the adjusted-SAR (***adjR$_{Na}$***) = 7.73 / ((1.44 + 1.43) / 2)$^{1/2}$ = 6.45.

- *Water 2*

    a. **SAR** = 11.75 / ((0.93 + 0.5) / 2)$^{1/2}$ = 13.90

    b. Adjusted-SAR (***adjR$_{Na}$***).

    1. [HCO$_3$$^-$] / [Ca^{2+}] = (5.65 + 0.88) / 0.93 = 7.02

    2. From **Table 4**, for a ratio of 7 and an EC of 1.5, the [Ca$_x$$^{2+}$] is 1.43 meq/L.

    3. Therefore, the adjusted-SAR (***adjR$_{Na}$***) = 11.75 / ((0.59 + 0.5) / 2)$^{1/2}$ = 15.92.

Classification of Irrigation Water Based on SAR or adjR$_{Na}$

A general classification of irrigation water based upon SAR or adjR$_{Na}$ values are presented in Table 6.

Table 6. The sodium hazard of irrigation water based on SAR or adjR$_{Na}$ values.

SAR or adjR$_{Na}$ Values	Sodium Hazard of Water	Comments
1—10	LOW	Use caution on sodium sensitive crops such as avocados.
10—13	MEDIUM	Requires amendments (such as Gypsum) and leaching.
18—26	HIGH	Generally not recommended for continued use.
Above 26	VERY HIGH	Generally unsuitable for irrigation.

SAR or adjR$_{Na}$ and EC$_W$

At a given SAR or adjR$_{Na}$, the potential sodium hazard also depends on the salinity (EC$_W$) of irrigation water. So SAR or adjR$_{Na}$ should be used in conjunction with EC$_W$ to evaluate potential sodium hazard realistically.

At any given SAR or adjR$_{Na}$, as salt concentration decreases, there is a higher sodium hazard leading to reduced permeability of soils (Table 7).

Table 7. Guidelines for assessment of sodium hazard of irrigation water based on SAR or adjR$_{Na}$ and EC$_W$ (evaluate using EC$_W$ and SAR together) (Adapted from Ayres and Westcot. 1985; Miller and Gardiner, 2007).

Potential Irrigation Water Quality Problem	Degree of Restriction on Use		
	None	Slight to Moderate	Severe
	EC$_W$ (mmhos/cm or dS/m)		
When SAR or adjR$_{Na}$ = 0–3 and EC$_W$	> 0.7	0.2–0.7	< 0.2
When SAR or adjR$_{Na}$ = 3–6 and EC$_W$	> 1.2	0.3–1.2	< 0.3
When SAR or adjR$_{Na}$ = 6–12 and EC$_W$	> 1.9	0.5–1.9	< 0.5
When SAR or adjR$_{Na}$ =12–20 and EC$_W$	> 2.9	1.3–2.9	< 1.3
When SAR or adjR$_{Na}$ = 20–40 and EC$_W$	> 5.0	2.9–5.0	< 2.9

Soluble sodium percentage (SSP) in irrigation water is also used to evaluate its sodium hazard. The SSP is defined as the ratio of sodium in meq/L to the sum of all cations in meq/L multiplied by 100. An irrigation water with SSP greater than 60 percent may result in accumulation of sodium that will cause sodium hazards on soil properties as described earlier.

pH and Alkalinity

The pH value of water indicates whether it is acidic (pH < 7.0), neutral (pH ≈ 7.0), or alkaline (pH > 7.0). The normal pH range for irrigation water is 6.5 to 8.4 (Table 8). Acidic water (pH < 5.5) may cause accelerated corrosion of irrigation system.

Water with a high pH (> 8.5) is often caused by the presence of high amounts of bicarbonate and carbonate, known as alkalinity. High bicarbonate + carbonate binds calcium and magnesium ions and forms insoluble minerals. This enhances the hazardous effect of sodium on soil permeability. Thus alkaline water could intensify *sodium hazard*. In such cases, an adjusted SAR (adjR$_{Na}$) value rather than an ordinary SAR value, as discussed earlier, should be used to evaluate the potential *sodium hazard*. On the other hand, irrigation water with high pH and alkalinity may have some beneficial effects on the acidic soils of Georgia. However, this potential benefit has not yet been evaluated.

Specific Ion Toxicity and Miscellaneous Effects

In addition to salinity hazard and sodium hazard described earlier, saline irrigation water may lead to concentrations of some elements high enough to cause crop damage and reduce yields of sensitive crops, known as *Specific Ion Toxicity*. Sodium, chloride, and boron are of the most concern in this regard. Although these elements are essential to plants in very low amounts, they can cause toxicity to sensitive crops at high concentrations (Tables 8 and 9).

Table 8. Guidelines for assessment of specific ions toxicity and miscellaneous effects of irrigation water (Adapted from: Ayres and Westcot. 1985).

Potential Irrigation Water Quality Problem	Units	Degree of Restriction on Use		
		None	Slight to Moderate	Severe
Specific Ion Toxicity *(affects sensitive crops)*				
Sodium (Na)[1]				
Surface irrigation	mg/L or ppm	< 3	3–9	> 9
Sprinkler irrigation	mg/L or ppm	< 69	> 69	
Chloride (Cl)[1]				
Surface irrigation	mg/L or ppm	< 142	142–355	> 355
Sprinkler irrigation	mg/L or ppm	< 106	> 106	
Boron (B)[2]	mg/L or ppm	< 0.7	0.7–3.0	> 3.0
Miscellaneous Effects *(affects susceptible crops)*				
Nitrogen (NO$_3$ - N)[3]	mg/L or ppm	< 5	5–30	> 30
Bicarbonate (HCO$_3$) *(overhead sprinkling only)*	mg/L or ppm	< 92	92–519	> 519
pH		Normal Range 6.5–8.4		

[1] For surface irrigation, most tree crops and woody plants are sensitive to sodium and chloride; use the values shown. Most annual crops are NOT sensitive; use the salinity tolerance table (Table 3). For sodium and chloride tolerance of some selected crops, see Tables 9 and 10. With overhead sprinkler irrigation and low humidity (< 30 percent), sodium and chloride may be absorbed through the leaves of sensitive crops; for crop sensitivity to such absorption, see Table 10.

[2] For boron tolerances see Table 11.

[3] Nitrate-N means nitrate nitrogen reported in terms of elemental nitrogen (Ammonia-N and Organic-N should be included when wastewater is being tested for potential irrigation use).

Table 9. Relative tolerance of selected crops to sodium (Adapted from data of Pearson, 1960; FAO-UNESCO, 1973; Abrol, 1982; Ayers and Westcot, 1985).

Sensitive	Semi-Tolerant	Tolerant
• Avocado (*Persea americana*) • Deciduous Fruits • Nuts • Bean, green (*Phaseolus vulgaris*) • Cotton (at germination) (*Gossypium hirsutum*) • Corn (*Zea mays*) • Peas (*Pisum sativum*) • Grapefruit (*Citrus paradisi*) • Orange (*Citrus sinensis*) • Peach (*Prunus persica*) • Tangerine (*Citrus reticulata*) • Mung bean (*Phaseolus aurus*) • Lentil (*Lens culinaris*) • Groundnut (peanut) (*Arachis hypogaea*) • Chickpea (*Cicer arietinum*) • Cowpeas (*Vigna sinensis*)	• Carrot (*Daucus carota*) • Clover, ladino (*Trifolium repens*) • Dallisgrass (*Paspalum dilatatum*) • Tall fescue (*Festuca arundinacea*) • Lettuce (*Lactuca sativa*) • Bajara (*Pennisetum typhoides*) • Sugarcane (*Saccharum officinarum*) • Berseem (*Trifolium alexandrinum*) • Benji (*Melilotus parviflora*) • Raya (*Brassica juncea*) • Oat (*Avena sativa*) • Onion (*Allium cepa*) • Radish (*Raphanus sativus*) • Rice (*Oryza sativus*) • Rye (*Secale cereale*) • Ryegrass, Italian (*Lolium multiflorum*) • Sorghum (*Sorghum vulgare*) • Spinach (*Spinacia oleracea*) • Tomato (*Lycopersicon esculentum*) • Vetch (*Vicia sativa*) • Wheat (*Triticum vulgare*)	• Alfalfa (*Medicago sativa*) • Barley (*Hordeum vulgare*) • Beet, garden (*Beta vulgaris*) • Beet, sugar (*Beta vulgaris*) • Bermuda grass (*Cynodon dactylon*) • Cotton (*Gossypium hirsutum*) • Paragrass (*Brachiaria mutica*) • Rhodes grass (*Chloris gayana*) • Wheatgrass, crested (*Agropyron cristatum*) • Wheatgrass, fairway (*Agropyron cristatum*) • Wheatgrass, tall (*Agropyron elongatum*) • Karnal grass (*Diplachna fusca*)

Overhead Irrigation vs. Surface Irrigation

Overhead sprinkling on sensitive crops can cause toxicities not encountered when the same water is applied by surface or drip (surface or sub-surface) irrigation methods. The toxicity occurs due to excessive quantities of sodium and chloride from the irrigation water being absorbed through plant leaves. Extreme damage may include severe leaf burn and defoliation.

Toxicity to sensitive crops occurs at relatively low sodium or chloride concentrations (> 3 meq/L). Most annual crops are not sensitive, but they will also be damaged if concentrations are high enough. Absorption and toxicity occur mostly during periods of high temperature and low humidity (< 30 percent), and the problem is frequently made worse by windy conditions. Rotating sprinkler heads present the greatest risk. Between rotations, water evaporates and the salts become more concentrated in the shrinking volume of water. Crop tolerances to sodium and chloride in sprinkler-applied irrigation water are not well established due to limited data and the pronounced influence of climatic conditions. Table 10 gives some rough estimates.

Leaf burn under sprinkler from both sodium and chloride can be reduced by irrigating at nighttime or on cool, cloudy days. Drop nozzles and drag hoses are also recommended when applying any saline irrigation water through a sprinkler system to avoid direct contact with leaf surfaces.

Table 10. Relative tolerance of selected crops to foliar injury from saline water applied by sprinklers (Adapted from Maas, 1984; Ayers and Westcot, 1985)[1].

Concentrations Causing Foliar Injury[2]			
meq/L: < 5 (Na⁺ or Cl⁻) mg/L or ppm: Na⁺: < 115 Cl⁻: < 177	meq/L: 5–10 (Na⁺ or Cl⁻) mg/L or ppm: Na⁺: 115–230 Cl⁻: 177–354	meq/L: 10–20 (Na⁺ or Cl⁻) mg/L or ppm: Na⁺:230–460 Cl⁻: 354–708	meq/L: > 20 (Na⁺ or Cl⁻) mg/L or ppm: Na⁺: > 460 Cl⁻: > 708
Almond (*Prunus dulcis*)	Grape (*Vitis* spp.)	Alfalfa (*Medicago sativa*)	Cauliflower (*Brassica oleracea*)
Apricot (*Prunus armeniaca*)	Pepper (*Capsicum annuum*)	Barley (*Hordeum vulgare*)	Cotton (*Gossypium hirsutum*)
Citrus (*Citrus* sp.)	Potato (*Solanum tuberosum*)	Corn (maize) (*Zea mays*)	Sugarbeet (*Beta vulgaris*)
Plum (*Prunus domestica*)	Tomato (*Lycopersicon lycopersicum*)	Cucumber (*Cucumis sativus*)	Sunflower (*Helianthus annuus*)
		Safflower (*Carthamus tinctorius*)	
		Sesame (*Sesamum indicum*)	
		Sorghum (*Sorghum bicolor*)	

[1] Susceptibility based on direct accumulation of salts through the leaves. For some crops, the concentration given may exceed the overall salinity tolerance of that crop and cause some reduction in yield in addition to that caused by chloride ion toxicities.

[2] Leaf absorption and foliar injury are influenced by cultural and environmental conditions such as drying winds, low humidity, speed of rotation of sprinklers, and the timing and frequency of irrigations. Data presented are only general guidelines for late spring and summer daytime sprinkling.

Boron Toxicity

Boron may be toxic on sensitive crops at concentrations lower than 1.0 ppm in irrigation water (Table 11). Because boron toxicity can occur at such low concentrations, testing boron in irrigation water is recommended before applying additional boron to crops.

Table 11. Relative tolerance of selected crops to boron in irrigation water (Adapted from data of Maas, 1984; Ayers and Westcot, 1985)[1].

Very Sensitive (< 0.5 mg/L)		Sensitive (0.5–0.75 mg/L)	
Lemon	*Citrus limon*	Avocado	*Persea americana*
Blackberry	*Rubus* spp.	Grapefruit	*Citrus X paradisi*
Sensitive (0.75–1.0 mg/L)		Orange	*Citrus sinensis*
Garlic	*Allium sativum*	Apricot	*Prunus armeniaca*
Sweet potato	*Ipomoea batatas*	Peach	*Prunus persica*
Wheat	*Triticum eastivum*	Cherry	*Prunus avium*
Barley	*Hordeum vulgare*	Plum	*Prunus domestica*
Sunflower	*Helianthus annuus*	Persimmon	*Diospyros kaki*
Bean, mung	*Vigna radiata*	Fig, kadota	*Ficus carica*
Sesame	*Sesamum indicum*	Grape	*Vitis vinifera*
Lupine	*Lupinus hartwegii*	Walnut	*Juglans regia*
Strawberry	*Fragaria* spp.	Pecan	*Carya illinoiensis*
Artichoke, Jerusalem	*Helianthus tuberosus*	Cowpea	*Vigna unguiculata*
Bean, kidney	*Phaseolus vulgaris*	Onion	*Allium cepa*
Bean, lima	*Phaseolus lunatus*		
Groundnut/peanut	*Arachis hypogaea*		
Moderately Sensitive (1.0–2.0 mg/L)		**Moderately Tolerant (2.0–4.0 mg/L)**	
Pepper, red	*Capsicum annuum*	Lettuce	*Lactuca sativa*
Pea	*Pisum sativa*	Cabbage	*Brassica oleracea*
Carrot	*Daucus carota*	Celery	*capitata*
Radish	*Raphanus sativus*	Turnip	*Apium graveolens*
Potato	*Solanum tuberosum*	Bluegrass, Kentucky	*Brassica rapa*
Cucumber	*Cucumis sativus*	Oats	*Poa pratensis*
Tolerant (4.0–6.0 mg/L)		Maize	*Avena sativa*
Sorghum	*Sorghum bicolor*	Artichoke	*Zea mays*
Tomato	*Lycopersicon*	Tobacco	*Cynara scolymus*
Alfalfa	*lycopersicum*	Mustard	*Nicotiana tabacum*
Vetch, purple	*Medicago sativa*	Clover, sweet	*Brassica juncea*
Parsley	*Vicia benghalensis*	Squash	*Melilotus indica*
Beet, red	*Petroselinum crispum*	Muskmelon	*Cucurbita pepo*
Sugarbeet	*Beta vulgaris*		*Cucumis melo*
	Beta vulgaris	**Very Tolerant (6.0–15.0 mg/L)**	
		Cotton	*Gossypium hirsutum*
		Asparagus	*Asparagus officinalis*

[1] Maximum concentrations tolerated in soil-water or saturation extract without yield or vegetative growth reductions. Boron tolerances vary depending upon climate, soil conditions and crop varieties. Maximum concentrations in the irrigation water are approximately equal to these values or slightly less.

Miscellaneous Effects

Other problems associated with irrigation water include reductions in crop yield and quality due to excessive nutrients; hindered marketability due to unsightly deposition of excessive nutrients on fruit or foliage; and increased maintenance and repair costs due to clogging or excessive corrosion of equipment. Irrigation waters high in nitrogen—when applied with recommended dose of N fertilizer—can cause quality problems in crops, such as malting barley and sugar beets, and excessive vegetative growth in some vegetables. However, good fertilizer and irrigation water management can usually solve these problems. Irrigation water nitrate-nitrogen should be credited toward the fertilizer rate especially when the concentration exceeds 10 ppm nitrate-nitrogen (or 45 ppm nitrate). Table 12 includes some useful irrigation water quality criteria to assess the clogging potential in drip irrigation systems.

Table 12. Water quality and clogging potential in drip irrigation systems (Adapted from Nakayama, 1982; FAO, 1992).

Water Quality Criteria	Unit	Degree of Restriction to Use		
		None	Slight to Moderate	Severe
Physical				
Total suspended solids (TSS)	mg/L	< 50	50–100	> 100
Chemical				
pH	none	< 7.0	7.0–8.0	> 8.0
Total dissolved solids (TDS)	mg/L	< 500	500–2,000	> 2,000
Manganese (Mn)	mg/L	< 0.1	0.1–1.5	> 1.5
Iron (Fe)	mg/L	< 0.1	0.1–1.5	> 1.5
Hydrogen sulfide (H_2S)	mg/L	< 0.5	0.5–2.0	> 2.0
Bacteria	MPN/mL[1]	< 10,000	10,000–50,000	> 50,000

[1] MPN = Most Probable Number

Bacteria in Irrigation Water

The water used for irrigation and crop protection (spraying insecticides and herbicides) by the producers of fresh fruits and vegetables in Georgia are required to meet the specifications set by Good Agricultural Practices (GAP) audit by the Georgia Department of Agriculture (GDA) sanctioned in 2005. A key area of the Georgia GAP audit is bacteriological water quality compliance. The main goal of irrigation water quality compliance in this regard is to ensure the required bacteriological quality of water used in Georgia for irrigation and crop protection that could allow growers to make informed decisions on how to use their water safely. However, standards for this have not yet been developed and implemented by the state.

In the absence of a state approved standard, the microbial quality of irrigation water is being evaluated following "The Commodity Specific Food Safety Guidelines for the Production and Harvest of Lettuce and Leafy Greens" (July/10/2009). The guidelines recommend:

- The geometric mean of five consecutive samples (*collected at least 18 hours and at most 30 days apart*) tested for the bacterium *Escherichia coli (E. coli)* should not exceed 126 MPN/100 mL for both foliar and non-foliar applications.

- When the sampling criteria for the geometric mean, stated above, are followed and the recommended level for the geometric mean is met, any single sample *E. coli* level should not exceed 235 MPN/100 mL for foliar application (sprinkler) and 576 MPN/100 mL for non-foliar application (drip/furrow).

However, given the absence of any government adopted standards, the actual acceptance of the results relies entirely on the policy of the auditing body.

Calculation of Geometric Mean

The geometric mean of the observations X_1, X_2, X_3 ……………X_n is given by: $\sqrt[n]{X_1 X_2 X_3 X_4 \ldots X_n}$

Suppose, you collected five water samples at least 18 hours and at most 30 days apart, tested them for *E. coli*, and you found these concentrations:

Sample Number	E. coli (MPN or CFU per 100 mL)[1]
1	10
2	100
3	300
4	15
5	4

[1] MPN = Most Probable Number; CFU = Colony Forming Unit. MPN and CFU are interchangeably used and interpreted on the same standard.

The geometric mean for these data is as follows: $\sqrt[5]{10 \times 100 \times 300 \times 15 \times 4} = 28.25$

IMPORTANT NOTE: The U.S. Food and Drug Administration (FDA) Food Safety Modernization Act (FSMA) was signed into law by the president on January 4, 2011. The FDA, Center for Food Safety (CFS), and the Center for Environmental Health (CEH) are going to publish the final rules pertinent to produce safety required for implementing the FSMA in this regard. These rules will include the "Standards Directed to Agricultural Water" within the "Standards for the Growing, Harvesting, Packing, and Holding of Produce for Human Consumption." *This section will be revised based on the final rules once they are published.*

Summary

The nature and extent of irrigated agriculture has changed with respect to water quantity and quality over the past 30 years. In fact, irrigated acreage in Georgia has increased tremendously and is expected to surpass 1.65 million irrigated acres by 2050. With this increase in water use, the availability of water and the quality of water will continue to be a concern in the coming years. Producers must take this into consideration when planning and using irrigation systems.

Understanding irrigation water quality is critical to making management decision for long-term productivity since it can have a significant effect on crop yield, physical condition of the soil, soil salinity, fertility needs, irrigation system performance (and longevity), and water application methods. In some cases, the quality of irrigation water can influence crop productivity more than soil fertility, plant cultivar, or weed control. Maintaining water quality in an irrigation system is vital to the system's effectiveness and can mean the difference between a below average yield and a bumper crop.

Glossary of Terms (Adapted from Hanson et al., 2006)

Electrical conductivity. Defines the extent to which water conducts electricity, which is proportional to the concentration of dissolved salts present and is used as an estimator of the total dissolved salts in soil water. Electrical conductivity is expressed in millimhos per centimeter (mmhos/cm) or decisiemens per meter (dS/m):
EC_e = electrical conductivity of the saturated soil extract.
EC_i, EC_{iw}, or EC_w = electrical conductivity of the irrigation water.
EC_{sw} = electrical conductivity of the soil water.

Saline soil. Soil affected by excessive salts.

Saline-sodic soil. Soil affected by both excessive salts and excessive sodium.

Salinity hazard. Inadequate water uptake by plants due to high salts concentration in soil water.

Salinity. The measure of salt contained in soil or water.

Sodic Soil. Soil affected by excessive sodium.

Sodicity. Condition in which the salt composition of the soil or water is dominated by sodium, which affects soil structure and water infiltration.

Sodium adsorption ratio (SAR). Relationship between the concentration of sodium ($[Na^+]$) in the irrigation water relative to the concentrations of calcium ($[Ca^{2+}]$) and magnesium ($[Mg^{2+}]$), expressed in meq/L as follows:

$$SAR = \frac{[Na^+]}{\sqrt{\frac{1}{2}([Ca^{2+}] + [Mg^{2+}])}}$$

Sodium hazard. Reduction or loss of water permeability of soil due to destruction of soil structure caused by excessive sodium relative to calcium and magnesium.

Specific-ion toxicity. Injury to the plant caused by a specific constituent in irrigation water, usually chloride, boron, or sodium, which has accumulated in a particular part of the plant, such as leaves and stems.

Total dissolved solids (TDS). A measure of the dissolved solids in soil water, expressed in either parts per million or milligrams per liter, used to estimate the relative salinity hazard of the water.

For more information on irrigation water quality, contact your local Cooperative Extension agent at 1-800-ASK-UGA1.

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