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Does Turbulent-Flow Conditioning of Irrigation Water Influence Soil Chemical Processes: I. Laboratory Results

Rodrick D. Lentz

USDA-ARS Northwest Irrigation and Soils Research Laboratory, Kimberly, Idaho, USA

ABSTRACT

Researchers commonly assume that the intrinsic behavior of molecular water is invariable, yet accumulating evidence suggests that water behavior can be modified via non-chemical means, e.g. by magnetic field effects. This laboratory study examined the effect of turbulent-flow conditioning (CTap) of a mineralized irrigation water source (Tap water) on water chemistry and the behavior and character of soil–water interactions. Turbulent conditioning did not alter the chemistry of water itself; dissolved organic and inorganic carbon, nitrate, ammonium, chloride, dissolved oxygen, and nutrient element concentrations were the same both before and after treatment. However, turbulent conditioning slightly reduced the surface tension of CTap water relative to Tap. Results indicate that CTap irrigation water changed the chemical composition in one pore volume of water leached through the soil column; consistently increasing mean potassium, ammonium, magnesium, and calcium concentrations by 1.2- to 1.4-fold compared to untreated Tap water. Results for the micro-nutrients were inconclusive because their concentrations in the waters were below the analytical detection limit. Conditioning may have changed physical properties of the CTap water, which altered the nature of its physical and/or chemical interactions with the soil. A consistent effect develops after incubated soil is irrigated for >4-weeks, suggesting that the treatment impacts on soil properties may accumulate over time, potentially influencing soil productivity and management. This phenomenon deserves to be further investigated; if the capacity of this simple device to increase soil cation leaching can be confirmed, it could potentially provide an economical means of managing salt-affected soils.

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Introduction

Irrigation water may interact with accumulated minerals and salts in soils and negatively influence soil and groundwater quality and crop productivity (Bohn, McNeal, and O'Connor 1985; Schwab, Fangmeier, and Elliot 1996). Research examining such processes has focused mainly on the chemistry and quantity of water applied (Al-Ghobari, 2011; Amundson and Smith 1988; Bauder and Brock 2001; Nunes et al. 2007). The effects of non-saline, saline, and alkali irrigation water on salt accumulation in soils, aggregate stability, infiltration, and erosion are well understood. Some research has shown that physical water treatment, which does not directly alter the chemical concentrations of irrigation water itself, can also influence soil–water interactions. For example, mineralized water flowing through a magnetic field can be altered with respect precipitation reactions and other characteristics (Chibowski and Szcześ 2018; Fathi et al. 2006). This has led to industrial applications for reducing scale formation in industrial heat exchangers and boilers (Alabi et al. 2015) and initial research into

CONTACT Rodrick D. Lentz rk_lentz@netzero.com USDA-ARS Northwest Irrigation and Soils Research Laboratory, 3793 N 3600 E, Kimberly, ID 83341

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magnetized water effects on water and salt movement in soils (Hamza 2019; Noran, Shani, and Lin 1996; Surendran, Sandeep., and Joseph 2016). Though it has been in existence for a century or more, the efficacy of magnetic water treatment technology is the subject of much debate, primarily because its theoretical basis and factors influencing its functionality have not been well understood (Ghernaout 2018). A related and parallel debate has churned, also for more than a century, regarding the 3-dimensional configuration of hydrogen-bonded liquid water (Clark et al. 2010; Shi and Tanaka 2020). Both these situations reveal considerable voids in our fundamental understanding of water behavior.

Turbulent-flow water conditioning is a less known and even less studied process that is hypothesized to alter water activity in a manner roughly analogous to that of magnetic water conditioning. Irrigation water may be applied to soils under low- or high-turbulent conditions. Surface irrigation spreads water over the soil under non-turbulent (low Reynold's Number) gravity-driven flow (i.e., basin, border, or furrow), a less agitative alternative to pressurized sprinkler applied water, which is subjected to high shear forces as it is propelled at elevated velocities through the pump, distribution pipes, sprinkler orifices, and then impact plates all under high flow (high Reynold's Number) conditions. Ippolito et al. (2018) compared soil properties of a calcareous, flood-irrigated soil with those of adjacent and similarly managed soils that had been sprinkler-irrigated for 5 to 8 yr. Even though both soils were irrigated using the same water source, they exhibited different surface soil chemical properties. The differences were attributed to disparities in soil water saturation and reducing conditions, but soil redox potentials were not measured to confirm this hypothesis (Ippolito et al. 2019). However, others have not observed saturated conditions (soil-water potential > -0.20 kPa) beneath irrigation furrows in well-drained soils such as these (North 2012; Segeren and Trout 1991). Furthermore, anecdotal observations of soils irrigated with turbulent conditioned water suggested that the treated water positively impacted plants grown in semiarid, calcareous soils (Josh Ferber, personal communication, 2009).

The objective of this laboratory research was to determine whether turbulent-flow-treated source water interacts differently with soil than unconditioned water. The study applied the two types of source water in equal volumes to individual soil columns under identical environmental conditions and evaluated turbulent water conditioning effects on the chemistry of 1) produced water; 2) water extracted from soil after a short mixing period; and 3) leachate from irrigated soil columns incubated in the laboratory for several weeks.

Materials and methods

Soil obtained near Kimberly, Idaho, USA (42E 31′ N, 114E 22′ W, elevation of 1190 m) was collected from the 0 to 15 cm depth in an eroded Portneuf silt loam (coarse-silty, mixed superactive, mesic Durinodic Xeric Haplocalcids). The soil was air-dried, screened through a sieve with 2-mm openings, and mixed thoroughly. Soil properties are reported in Table S1. The soil's coarse clay fraction is dominated by weathered or hydrous mica (50–60%) and includes 10–20% kaolinite and 10–15% montmorillonite (McDole and Maxwell 1966).

Tap water was used in the experiment instead of distilled water because its chemistry more closely matched that of local irrigation water and did not require the construction of a separate pressurized water supply. The turbulent-flow-inducer, water conditioning device employed tap water under typical domestic water pressures. The cylindrical device directed water flow through a series of diverging and converging pathways, similar to that occurring when water flows through a bed of spherical bodies (Vennard and Street 1982; Clayton Nolte, personal communication, 2010). A simple plumbing system made from 20-mm PVC tube directed a flow of laboratory tap water either through the turbulent-flow-inducer or through a normal tube (Fig. S1). At domestic water pressures, the flows within both the turbulent-flow inducer and the normal tube generated turbulent flows having superficial velocities of 1.8 m s^{-1} but the Reynolds number for flow in the normal tubewas 30000 to 35000 while that in the turbulent-flow inducer was 50000 to 55000 (Jolls and

Hanratty 1966; Vennard and Street 1982). Volumes of the two water types used in treatments were simultaneously produced by alternating the flow of source water from one path to the other. This limited potential bias caused by temporal changes in system water chemistry and provided freshly conditioned tap water to each experimental unit. Before treatment waters were produced, the tap was opened for 5 to 10 minutes to flush stagnant water from the laboratory supply pipes. The laboratory water was supplied via pump from local groundwater and was not treated with chlorine or other disinfectants.

Experiment one: characterization of conditioned water

This study included three separate assessments to determine the influence of turbulent conditioning on 1) tap water chemistry; 2) dissolved oxygen; and 3) surface tension. The first conducted a series of five tests over a 17-mo period. In each test, five to ten paired samples of tap and conditioned-tap water were produced. Each treatment response was computed as the test mean. A portion of these samples were immediately analyzed for electrical conductivity (EC),

pH, and dissolved inorganic carbon (DIC). The remaining samples were stabilized with a saturated boric acid (H_3BO_3) solution and stored at 4°C for <10 days prior to nutrient and elemental analysis. The water samples contained no sediment and required no filtration. The DIC and dissolved organic carbon (DOC), as non-purgeable organic carbon were determined using a Shimadzu TOC-L (Shimadzu Scientific Instruments, Columbia, MD). Sample nitrate nitrogen (NO_3-N), ammonium nitrogen (NH_4-N) and choride (Cl) concentrations were determined using an automatic, colorimetric flow injection analyzer (FIA) (Lachat Instruments, Loveland, CO), and calcium (Ca), potassium (K), magnesium (Mg), sodium (Na), phosphorus (P), sulfur (S), iron (Fe), zinc (Zn), manganese (Mn), and aluminum (Al) concentrations using inductively coupled plasma atomic emission spectrometry (ICP-AES) (PerkinElmer, American Fork, UT). The dissolved oxygen (DO) assessment conducted a series of four tests over a 14-mo period, where each test included four paired tap water samples of the two treated waters. After each water was produced, it was placed in an entirely filled, capped bottle. The DO of the samples was immediately determined using an azide modification of the iodometric (Winkler) method [4500-O OXYGEN (DISSOLVED) (2017) Standard Methods For the Examination of Water and Wastewater 10.2105/SMWW.2882.091 https://www.standardmethods.org/doi/abs/10.2105/SMWW.2882.09]. The surface tension evaluation consisted of a series of seven tests conducted over 8 days, where each test included four paired samples of the two treated waters. After each pair of water samples was produced, their surface tensions were measured using a Krüss Processor Tensiometer K12 (KRÜSS USA, Matthews, NC). Water temperatures of the paired samples during measurement differed by less than 0.2°C. on average.

Experiment two: soil extraction

This trial determined whether the soil chemical determinations would be influenced by the type of water used to extract the soil. Either tap or conditioned waters were employed as the extractant. A series of four separate tests were conducted over a 15-mo period. Four to ten paired samples of tap and conditioned-tap water were produced in each test. Half of each sample was analyzed (see below) and the remainder used for extraction. The treatment response was the mean of each test. Portneuf soil and the water were mixed 1:1 (125 g soil and 125 mL water to a 250-mL bottle), agitated for 1 h on a reciprocating shaker (120 cycles min^{-1}), and the mixture filtered through a dual-media filter (Whatman #41 atop #42). Samples of extractants and filtrate were analyzed for the same analytes, using the same methods listed in the tap water chemistry test (Exp. 1), with the exception that filtrate samples were not stabilized, but instead were stored at 4°C. The FIA analyses were completed within

6 h of extraction. The ICP subsamples were prepared directly from filtrate but the remaining water was filtered again (pre-rinsed 0.45-µm) for DIC and DOC analyses and all were completed within 48 h of extraction.

Experiment three: 6-week incubation w/ or w/o plants

This experiment examined the effect of water conditioning and plants on leachate water quality after soil and water had interacted for 6 weeks. The experimental design was completely randomized with four treatments and seven replications. Treatments included either planted or fallow soils supplied with either tap- or conditioned-tap water. Each experimental unit consisted of a 40-mm inside diameter by 131-mm-long PVC cylinder containing Portneuf soil that was subject to one of four treatments (4 treatments by 7 replicates for a total of 28 units). The base of each column was fitted with a nylon-mesh closure and packed with 205-g soil in three lifts, with tamping, to a bulk density of 1.31 g cm^{-3}. One-half of the columns were randomly assigned to the tap water treatment and the other half to the CTap treatment. All water added to the columns, except for the 5-mL fertilizer application (see below), matched that of the assigned treatment. Soil columns were slowly saturated from the below with suitably treated water, pore volumes were determined, and soils allowed to drain for 24 h. Each column then received 30 kg N ha^{-1} as ammonium nitrate (NH_4NO_3) in 5 mL RO water. Three barley (*Hordeum vulgare* L.) seeds (later thinned to one seedling per column) were planted in half the columns for each water-treatment. A randomized array of planted columns was placed under a grow light (12-h light per 24 h) at 22.2°C to 25.1°C. Unplanted soil columns were randomized and placed in a covered container nearby. Every 3 to 4 days, the soil columns were weighed and a suitably treated water was added to keep soil water content at 55% of pore volume. This water content was selected to inhibit denitrification. After 6-wk, the soil water content in columns was increased over 3 days in preparation for an induced leaching event. Then, just enough water was added to each soil column to produce one pore volume of leachate. The leachate was passed through a pre-rinsed Whatman #42 filter paper and samples were analyzed as in Exp. 2. Infiltration and leaching rates varied widely among soil columns in Exp. 3. The tamping procedure used to pack soils apparently created compact soil lenses in some columns that slowed drainage. As a result, the time required collect a single pore volume ranged from 4 to 12 days among the 28 columns. To ensure that the drainage rate had not biased our results, the incubation study was repeated (as Experiment 4).

Experiment four: 8-week incubation – no plants

This experiment was like Exp. 3 except: *i*) a different sample of eroded Portneuf soil was collected; *ii*) columns were filled with 182 g soil to a bulk density of 1.26 g cm^3 by tapping the cylinder on the counter 5 five times (no tamping); *iii*) no plants were grown in soils nor fertilizer applied; and *iiii*) the completely randomized experimental design included tap and conditioned water treatments and ten replicates (20 experimental units). The incubation and leaching procedures were the same as those used in Exp. 3, except that one pore volume leachate was collected 4-weeks, and a second pore volume 8-weeks, after the start of incubation. The same chemical procedures employed in Experiment 3 measured the same analytes in both leachate sample sets collected in Experiment 4.

Statistical analysis

In Experiment 1 and 2, we examined the influence of water treatment on individual tap water chemistry parameters, dissolved oxygen, or surface tension via analysis of variance (ANOVA) using PROC Mixed in SAS version 9.4 (SAS Institute Inc 2012). Water treatment was included as the fixed effect and test as the random effect. Individual leachate nutrient concentrations and properties in Experiments 3 were analyzed using ANOVA, PROC Mixed, with water treatment and planting as fixed effects and included contrast statements to assess effects of water treatment, planting, and their interaction on leachate parameters. Since water × plant interactions were not significant for any parameter in Experiment 3 ($P > .07$), leachate concentrations and property responses were averaged across the two plant treatments. These and Experiment 4 data were then analyzed via ANOVA with water treatment as the fixed effect and rep as random to determine water effects on individual parameters. Where needed to resolve nonconstant variance or improve distribution, responses were transformed prior to analysis, primarily using square root, and means were back-transformed to original units for reporting.

A multivariate methodology was used to test for water-treatment effects on overall leachate properties for each leaching event. The treatment comparisons included four steps: *i*) a stepwise discriminant analysis (SAS-PROC StepDisc) identified the subset of parameters that best discriminated between the two water treatment classes; *ii*) This parameter subset was employed in an overall one-way multivariate analysis of variance (MANOVA) using Wilk's likelihood ratio to test equality of mean vectors between classes. The procedure used SAS-PROC GLM where the MODEL was defined as "[parameter subset] = water treatment," and MANOVA tested the water treatment effect hypothesis with the residual matrix as the error; *iii*) If the hypothesis test was significant, simultaneous Bonferroni's confidence intervals were computed (Srivastava and Carter 1983) to investigate between-group differences for included variables; and *iiii*) Pearson Correlations computed by SAS-PROC CORR evaluated relationships of selected parameters with other parameters. Statistical analyses were conducted using a significance probability (P) of 0.05.

Results and discussion

Conditioned and extracted waters

Turbulent conditioning did not alter the chemical properties of treated tap water (Figure 1; Table S2), indicating that the diversion plumbing and conditioning apparatus neither differentially introduced contaminants, nor removed (adsorbed) elements/nutrients from, inflowing water. Results for the micronutrients were inconclusive because their concentrations in the waters were below the analytical detection limit. The DOC and P concentrations in both waters varied substantially (CVs >90%; (Figure 1)), indicating short-term and seasonal fluctuations in source-water DOC and P values. Water treatment had no effect on dissolved oxygen concentration, which was anticipated because oxygen cannot be introduced through the sealed plumbing or outer wall of the turbulence-inducing apparatus ($P = .6$). Turbulent conditioning did, however, slightly reduce the surface tension of the water from 72.2 mN m^{-1} to 71.7, a 0.7% decrease ($P = .01$). This small disparity may suggest potential effects of turbulence on the structural interaction between water molecules (Toledo et al. 2009). Or it is possible that, given the large deviations the water's DOC (Figure 1), the disparity was due to random variation in DOC concentrations for conditioned tap water (vs. tap water), which resulted in lower surface tension (Minofar et al. 2007; Nägali and Schanz 1991). However, this significant difference is important since alterations in surface tension can also impact other water properties such as viscosity (Pelofsky 1966).

Regardless of the type of extractant water used (tap water or CTap), water extracted from soil after 1 h mixing containeed identical element and nutrient concentrations and equivalent EC and pH properties (Figure 2, Table S3). Chemical characteristics of the two produced input waters again were the same, although the variability associated with DOC values continued to be relatively high (Table S3). The coefficients of variation (CVs) ranged from 3.4% to 46% for extractants within individual tests, and 4.3% to 10% for soil filtrates. There are two potential explanations for this lack of significant differences in extraction chemistries. The first is that the actual shaking motions (120 rev min^{-1}) created turbulent conditions which nullified the CTap differences in surface tension, thereby making both treatments similar due to transitional and

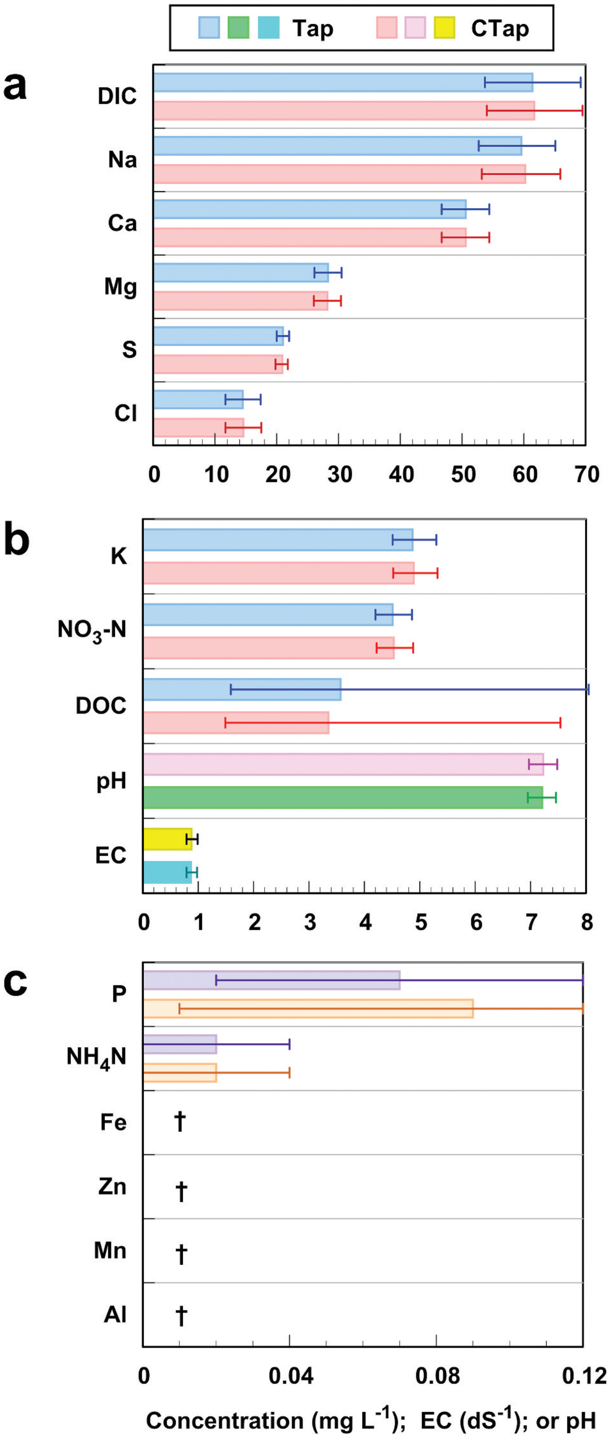

Figure 1. Experiment 1: Turbulent conditioning effects on water chemistry and properties. Treatments are unconditioned (Tap) and conditioned (CTap) tap water. Concentration units are mg L^{-1} and EC units are dS m^{-1}. Error bars represent 95% confidence limits on the means ($n = 5$). The symbol † indicates that measured mineral concentrations for one or more samples in each test were below analytical detection limits.

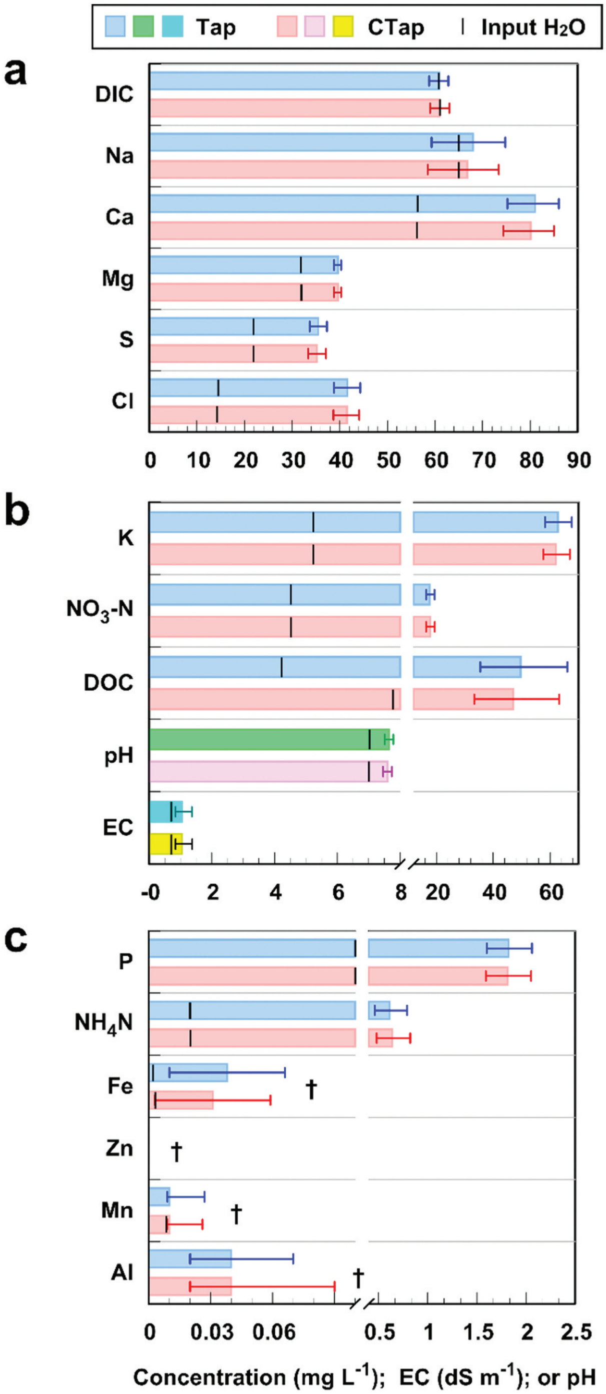

Figure 2. Experiment 2: Turbulent conditioning effects on extractant water (indicated by the vertical black line) and extracted filtrate after water and soil were mixed 1-h (colored bars). Extractant water was either unconditioned (Tap) and conditioned (CTap) tap water. Concentration units are mg L^{-1} and EC units are dS m^{-1}. Error bars represent 95% confidence limits on the means ($n = 4$) and † indicates that measured mineral concentrations for one or more samples in each test were below analytical detection limits.

turbulent mixing effects from shaking (Gardener and Tatterson 1992). Alternatively, it could be because the small differences in the water physical properties could take a longer time to manifest a statistically significant differences in nutrient extraction efficiencies (>1 h).

Characterization of leachate

Experiments 3 and 4 evaluated water treatment effects in soils when produced waters were added to soils over periods of four to 8 weeks. Each event collected one pore-volume leachate and collected volumes were similar between treatments ($P > .34$), making leachate chemistries comparable. In experiment 3, the water × plant interactions were not significant ($P > .07$), indicating that the effect of water conditioning on leachate chemistry was unchanged by the planting. From all leachate parameters describing each leaching event, stepwise discriminant analysis selected three or four that discriminated most between water treatments (Table 1). For each event, the MANOVA results were highly significant, indicating that mean vectors defined by the selected parameters differed due to water treatment (Table 1).

Leachate anions dominated discriminate parameter selections in the 4-week event (DIC, Cl, DOC), while cations dominated selections for the 6-week (pH, Al, NH_4-N, K) and 8-week (DOC, Ca, Na, Mg) events. At 4 weeks, CTap reduced DIC (11%) and Cl (30%) concentrations in leachate waters relative to the Tap treatment (Table 1). The negative correlations of Cl with NH_4-N and K at 4 weeks indicate that these cation concentrations increased in CTap leachate as Cl was reduced (Table 2). This was confirmed by ANOVA analyses conducted on individual components, which showed that CTap increased leachate NH_4-N 1.1-fold relative to Tap water (Table 3). Similarly, at 6 weeks, CTap increased leachate concentrations of discriminating cations, NH_4-N (2-fold) and K (1.3-fold), as well as increased leachate pH (1.01-fold), compared to Tap water (Table 1). The substantial positive correlation of K with Mg at 6 weeks suggests that CTap also increased leachate Mg concentrations (Table 2). This is corroborated by ANOVA analyses conducted on individual components, which showed that CTap increased Mg concentrations 1.3-fold relative to Tap water (Table 4).

At 8 weeks, CTap increased leachate concentrations of discriminating cations, Ca (1.4-fold) and Mg (1.3-fold) and increased DOC (1.2-fold), but decreased Na (21%) relative to Tap water (Table 1). The positive correlation of K and NO_3-N with DOC, Ca, and Mg (Table 2) also indicates that CTap increased leachate K and NO_3-N concentrations. This was confirmed by ANOVA analyses for individual components, showing that CTap increased leachate K 1.1-fold and NO_3-N 1.2-fold relative to Tap water (Table 3). Correlation analysis also showed that cation concentrations in leachate were positively related to anionic components DIC, DOC, NO_3-N, Cl, and S (mostly as sulfate) for the

Table 1. Mean values for parameters selected by discriminate analysis on water treatments, results of overall one-way manova testing for the equality of mean vectors using Wilk's likelihood ratio, and between-group mean comparisons for specific parameters derived from Bonferroni-adjusted confidence intervals on the means.

	4 weeks[†]			6 weeks			8 weeks	
	Treatment [†]			Treatment [†]			Treatment [†]	
Parameter	Tap	CTap	Parameter	Tap	CTap	Parameter	Tap	CTap
DIC	51.1 a [‡]	45.6 b	pH	8.12 b	8.22 a	DOC	11.8 b	13.6 a
Cl	83.5 a	58.1 b	NH_4-N	0.10 b	0.20 a	Ca	67.6 b	92.9 a
DOC	12.8	11.8	Al	0.007	0.007	Na	125 a	99.0 b
			K	77.5 b	103 a	Mg	27.3 b	34.8 a
MANOVA [§]	$P < .0001$		Manova	$P = .0006$		Manova	$P < .0001$	

[†] Tap = tap water; CTap = conditioned tap water

[‡] For each leaching event, water treatment means followed by the same letter are not significantly different ($P < 0.05$). No letters are listed if the comparison was not significant.

[§] Wilk's lambda tests hypothesis that group mean vectors for Tap and CTap treatments were equivalent.

Table 2. Pearson correlation coefficients and significance for parameters selected by discriminant analysis for each leaching event with other leachate component concentrations (mg l^{-1}) and properties, ec (ds m^{-1}) and pH.

Leachate Parameters	4 weeks†			6 weeks				8 weeks			
	DIC	Cl	DOC	pH	Al	NH_4-N	K	DOC	Ca	Na	Mg
DIC	1	0.55*	0.32	0.60***	0.41*	0.59***	0.57**	−0.58**	−0.60**	0.20	−0.64**
DOC	0.33	0.58**	1	0.43*	0.59***	0.61***	0.77***	1	0.43	0.30	0.58**
NH_4N	−0.23	−0.61**	−0.24	0.56**	0.38*	1	0.62***	0.57**	0.24	0.05	0.34
NO_3N	−0.26	0.38	0.51*	0.09	0.24	0.01	0.51**	0.79***	0.63**	0.26	0.74***
Ca	−0.11	−0.41	−0.26	0.32	0.27	0.38*	0.56**	0.43	1	−0.49*	0.97***
Na	0.06	0.33	0.27	0.55**	0.81***	0.57**	0.85***	0.30	−0.49*	1	−0.38
Mg	−0.09	−0.40	−0.30	0.38*	0.34	0.28	0.70**	0.58**	0.97***	−0.38	1
K	−0.25	−0.45*	−0.16	0.57**	0.60***	0.62***	1	0.77***	0.58**	0.33	0.64**
Cl	0.55*	1	0.58**	0.42*	0.71***	0.37	0.86***	0.91***	0.44	0.42	0.60**
S	0.08	0.34	0.25	0.57***	0.69***	0.69***	0.84***	0.93***	0.39	0.37	0.54*
P	0.15	0.28	0.37	−0.25	−0.12	−0.20	−0.29	−0.60**	0.25	−0.59**	0.10
pH	0.27	0.54*	0.09	1	0.47*	0.56**	0.57**	−0.66**	−0.82***	0.24	−0.87***
EC	0.60**	0.80***	0.72***	0.56**	0.66***	0.61***	0.92***	0.54*	0.30	0.12	0.41
Al †	.	.	.	0.47*	1	0.38*	0.60***	.	.	.	.
Fe †	.	.	.	0.44*	0.97***	0.37	0.60***	.	.	.	.
Zn †	.	.	.	.	.	.	.	.	.	.	.
Mn †	.	.	.	.	.	.	.	.	.	.	.

*, P#0.05 **, P#0.01 ***, P#0.001 ns, non significant

†Correlations not displayed if >30% of micronutrient concentration values fell below analytical detection limits.

Table 3. Experiment 4. Effects of turbulent conditioning on the chemistry of one pore-volume leachate water collected four and 8 weeks after the start of incubation. Included are the *p*-values testing treatment effects ($n = 10$).

	4 weeks			8 weeks		
	Water Type †			Water Type †		
Nutrient/element	Tap	CTap	*P*-value	Tap	CTap	*P*-value
DIC (mg L^{-1})	51.1	45.6	***	40.2	37.7	**
DOC (mg L^{-1})	12.8	11.8	ns	11.8	13.6	*
NH_4-N (mg L^{-1})	0.78	0.89	**	0.38	0.44	ns
NO_3-N (mg L^{-1})	24.1	23.2	ns	30.4	35.3	*
Ca (mg L^{-1})	57.9	70.2	ns	67.6	92.8	***
Na (mg L^{-1})	134	102	ns	125	99	**
Mg (mg L-1)	22.2	26.1	ns	27.3	34.8	***
K (mg L^{-1})	8.6	9.4	ns^{+}	13.2	14.6	*
Fe (mg L^{-1}) ‡	0.03	0.00	ns	0.001	0.001	ns
Zn (mg L^{-1}) ‡	0.00	0.00	ns	0.00	0.00	ns
Mn (mg L^{-1}) ‡	0.00	0.00	ns	0.00	0.00	ns
Al (mg L^{-1}) ‡	0.01	0.00	ns	0.00	0.00	ns
Cl (mg L^{-1})	83.5	58.1	***	77.4	84.6	ns
S (mg L^{-1})	52.0	46.1	ns	60.3	65.8	ns^{+}
P (mg L^{-1})	0.23	0.21	ns	0.18	0.19	ns
pH	8.26	8.04	*	8.7	8.6	***
EC (dS m^{-1})	1.20	0.99	***	1.22	1.29	ns

*, P#0.05 **, P#0.01 ***, P#0.001 ns, non significant ns^{+}, 0.05#P#0.10

†Tap = tap water; CTap = conditioned tap water.

‡Micronutrient concentrations for some replicates were below analytical detection limits.

6-week and 8-week events, which is logical since both cation and anion components must be leached together to maintain electrical neutrality (Table 2). Differences in water treatment leachate effects between the 4-week and later events may suggest a progressive component to CTap’s influence.

The response of leachate Na, DIC, Cl, pH, and EC chemistries to turbulent conditioning were contradictory across events; CTap increased response values relative to Tap in Experiment 3 but produced the opposite effect in Experiment 4. This response pattern suggests that other factors may be impacting these leachate concentrations. For example, the slow leaching rate in Experiment 3 (4–

Table 4. Experiment 3. Effects of turbulent conditioning and plant presence on the chemistry of one pore-volume leachate water collected 6 weeks after the start of incubation. Included are *p*-values testing factor and interaction effects. ($n = 7$).

	Water Type†		Plant status		Factor-interaction effects		
Nutrient/element	Tap	CTap	Fallow	Barley	Water	Plant	Water x Plant
DIC (mg L^{-1})	58.3 b	79.3 a	70.4	67.2	**	ns	ns
DOC (mg L^{-1})	33.8	40.4	33.5	40.6	ns^{+}	ns^{+}	ns
NH_4-N (mg L^{-1})	0.10 b	0.20 a	0.12 b	0.18 a	***	*	ns
NO_3-N (mg L^{-1})	29.3	33.6	27.3	25.0	ns	ns^{+}	ns
Ca (mg L^{-1})	65	83	58 b	68 a	ns^{+}	ns	ns
Na (mg L^{-1})	224 b	288 a	233	279	*	ns	ns
Mg (mg L^{-1})	35.7 b	45.2 a	47.1 b	33.8 a	*	**	ns
K (mg L-1)	77 b	103 a	92	88	**	ns	ns
Fe (mg L^{-1}) §	0.006	0.007	0.005	0.008	ns	ns	ns
Zn (mg L^{-1}) §	0.005	0.007	0.005	0.008	ns	ns	ns
Mn (mg L^{-1}) §	0.000	0.003	0.003	0.001	ns^{+}	ns	ns
Al (mg L^{-1}) §	0.010	0.012	0.010	0.012	ns	ns	ns
Cl (mg L^{-1})	57.6	68.3	63.5	62.5	ns	ns	ns
S (mg L^{-1})	85 b	113 a	93	105	*	ns	ns
P (mg L^{-1})	2.42	2.12	1.98	2.56	ns	**	ns
pH	8.13 b	8.22 a	8.18	8.17	**	ns	ns
EC (dS m^{-1})	1.82 b	2.62 a	2.25	2.19	*	ns	ns

*, *P*#0.05 **, *P*#0.01 ***, *P*#0.001 ns, non significant ns^{+}, 0.05#*P*#0.10

†Tap = tap water; CTap = conditioned tap water

‡For each water type and plant status comparison, means followed by the same letter are not significantly different ($P < 0.05$). No letters are listed if the ANOVA was not significant.

§Micronutrient concentrations for some replicates were below analytical detection limits.

12 days per pore volume vs. 2–3 days in Experiment 4) allowed for greater ion exchange, diffusion, and dissolution reactions between soil and water, resulting in greater leachate solute concentrations (Wiklander 1974). Furthermore, the prolonged wet conditions present during leaching in Experiment 3 likely increased soil-solution bicarbonate (HCO_3^-) (and hence DIC) concentrations and increased leachate pH (Bloom and Inskeep 1986).

Irrigating the eroded Portneuf soil with turbulent-flow-conditioned tap water instead of tap water resulted in an unambiguous increase in leached cations, K, Mg, and NH_4, with evidence that leaching of other cations and anions also may have increased, Ca, NO_3, S (mostly sulfate), and DOC. This implies that conditioning increased the concentrations of these components in the soil solution (Wiklander 1974). Such increases could result from several processes: increased weathering of soil minerals or decomposition of organic matter; increased solubility of a precipitated solid phase; the release or replacement of cations or anions associated with the soil exchange complex; or increased desorption of ions from the solid–liquid phase interface (Sposito 1984; Wiklander 1974). Due to the requirement for electrical neutrality, CTap's influence on leachate anionic-species concentrations may be indirectly related to its effect on cations. Cations leached from soil are attended by a mass of leached anions with an equal and opposite cumulative charge (Lehmann and Schroth 2003). Hence, the types of anions leached during a given event may be related to changes in their availability and mobility. For example, if the highly mobile nitrate anion is in short supply, chloride may dominate the charge-balancing function in the leachate (Montagnini, Haines, and Swank 1991; Waring and Running 2007). Similarly, the effect of prolonged wet conditions during leaching in Experiment 3 on soil-solution HCO_3^- concentration probably made this anion more susceptible to coupled-charge losses (Bloom and Inskeep 1986).

The exact mechanisms by which CTap alters leachate water chemistry cannot be conclusively demonstrated from this study. The only statistically significant difference between measured water properties was the slight decrease in surface tension of CTap relative to Tap water. Although, not a large numeric difference, this would be manifested in decreased strength of cohesive forces between water molecules (Vennard and Street 1982) and could alter the viscosity of the infiltrating liquid (Pelofsky 1966). Either of these effects could change how conditioned water physically or chemically interacts with soil, even though the chemistry of the irrigation water itself is unchanged by treatment. Results indicate that the process is time sensitive, requiring a period of several days to produce a significant effect. This suggests that the effect of turbulence treatment on water behavior is relatively stable. Thus, soils treated with CTap irrigation water over extended periods may undergo measurable changes in soil chemistry, which may potentially influence their management and productivity.

Many soil scientists, like myself initially, may find the results of this study too remarkable. It is important to remember that the experimental units were treated identically except for the turbulent conditioning applied to the CTap water. The large number of replicates employed should have protected against the possibility that random variation in the soil chemical or physical properties in soil columns could have produced these outcomes, and it is unlikely that independently conducted Experiments 3 and 4 would have produced similar results if some random alignment of soil properties had resulted in the observed differences. Furthermore, if we refuse to attribute the leaching results to turbulent conditioning, we must still explain why leaching responses did not parallel those of the soil extraction experiment (#2), which clearly demonstrated no treatment effect. In either case, a previously unidentified phenomenon appears to be at work here, which should be further investigated. Of special interest, is whether turbulent conditioning effects are perceptible outside the precisely controlled environmental conditions of the laboratory. This is the question addressed in a companion article (part II), which reports on a 9-year, outdoor pot study that evaluated turbulent conditioning effects on leachate, soil properties, crop yields, and plant nutrient uptake. In addition, turbulent-flow-conditioning, because of its apparent capacity to increase soil cation leaching, may represent more than just an idle curiosity; hypothetically, it could provide an economic means of managing or remediating degraded and marginal soils (Hamza 2019).

Conclusions

This study reports the first evidence that turbulent-flow-conditioning modifies the character of soil-water reactions and alters the chemical composition of leachate relative to untreated water. The effect developed over a period of weeks, suggesting that the treatment impacts on soil properties may accumulate over time, potentially influencing soil productivity and management. However, the treatment's contradictory effects on leachate DIC, Na, and Cl concentrations, pH, and EC need to be further clarified. Further research is warranted to 1) confirm results of this primary discovery in other soils; 2) determine if similar results can be obtained in outdoor studies; 3) evaluate potential long-term effects on soil chemistry, nutrient status, and plant uptake; and 4) investigate mechanisms responsible for the phenomenon. Treatment effects on micronutrients were inconclusive due to their low concentrations in leachate, but gaged by the response of other cations, micronutrients should continue to be monitored in extended-term studies, as long-term effects may prove more substantive.

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ORCID

Rodrick D. Lentz http://orcid.org/0000-0003-2537-1628

References

Alabi, A., M. Chiesa, C. Garlisi, and G. Palmisano. 2015. Advances in anti-scale magnetic water treatment. *Environmental Science: Water Research & Technology* 1 (4):408–25. doi:10.1039/C5EW00052A.

Al-Ghobari, H. M. 2011. The effect of irrigation water quality on soil properties under center pivot irrigation systems in central Saudi Arabia. *Transactions on Ecology and the Environment* 145:507–16.

Amundson, R. G., and B. S. Smith. 1988. Effects of irrigation on the chemical properties of a soil in the western San Joaquin valley. *California Arid Land Research and Management* 2:1–17.

Bauder, J. W., and T. A. Brock. 2001. Irrigation water quality, soil amendment, and crop effects on sodium leaching. *Arid Land Research and Management* 15 (2):101–13. doi:10.1080/15324980151062724.

Bloom, P. R., and W. P. Inskeep. 1986. Factors affecting bicarbonate chemistry and iron chlorosis in soils. *Journal of Plant Nutrition* 9 (3):215–28. doi:10.1080/01904168609363438.

Bohn, H. L., B. L. McNeal, and G. A. O'Connor. 1985. *Soil Chemistry*. New York: John Wiley & Sons.

Chibowski, E., and A. Szcześ. 2018. Magnetic water treatment—A review of the latest approaches. *Chemosphere* 203:54–57. doi:10.1016/j.chemosphere.2018.03.160.

Clark, G. N. I., C. D. Cappa, J. D. Smith, R. J. Saykally, and T. Head-Gordon. 2010. The structure of ambient water. *Molecular Physics* 108:1415–33. doi:10.1080/00268971003762134.

Fathi, A., T. Mohamed, G. Claude, G. Maurin, and B. A. Mohamed. 2006. Effect of magnetic water treatment on homogeneous and heterogeneous precipitation of calcium carbonate. *Water Research* 40 (10):1941–50. doi:10.1016/j.watres.2006.03.013.

Gardener, J., and G. Tatterson. 1992. Characterization of mixing in shaker table containers. *Biotechnology and Bioengineering* 39 (7):794–97. doi:10.1002/bit.260390713.

Ghernaout, D. 2018. Magnetic field generation in the water treatment perspectives: An overview. *Internatioanl Journal of Advance and Applied Sciences* 5 (1):193–203. doi:10.21833/ijaas.2018.01.025.

Hamza, J. N. 2019. Investigation on using magnetic water technology for leaching high saline-sodic soils. *Environmental Monitoring and Assessment* 191 (8):519. doi:10.1007/s10661-019-7596-8.

Ippolito, J. A., D. L. Bjorneberg, S. W. Blecker, and M. S. Massey. 2019. Mechanisms responsible for soil phosphorus availability differences between sprinkler and furrow irrigation. *Journal of Environmental Quality* 48 (5):1–10. doi:10.2134/jeq2019.01.0016.

Ippolito, J. A., D. L. Bjorneberg, D. Stott, and D. Karlen. 2018. Soil quality improvement through conversion to Sprinkler irrigation. *Soil Science Society of America Journal* 81:1505–16. doi:10.2136/sssaj2017.03.0082.

Jolls, K. R., and T. J. Hanratty. 1966. Transition to turbulence for flow through a dumped bed of spheres. *Chemical Engineering Science* 21 (12):1185–90. doi:10.1016/0009-2509(66)85038-8.

Lehmann, J., and G. Schroth. 2003. Nutrient leaching. In *Trees, crops, and soil fertility: Concepts and research methods*, ed. G. Schroth and F. L. Sinclair, 151–66. Wallingford, UK: CAB International.

McDole, R. E., and H. B. Maxwell. 1966. *Soil survey: University of Idaho Research and Extension Center and USDA Snake River Conservation Research Center Kimberly*. Moscow. Idaho, USA: University of Idaho Agricultural Experiment Station. (Idaho Bulletin 656).

Minofar, B., P. Jungwirth., R. R. Das, W. Kunz, and S. Mahiuddin. 2007. Propensity of formate, acetate, benzoate, and phenolate for the aqueous solution/vapor interface: Surface tension measurements and molecular dynamics simulations. *Journal of Physical Chemistry C* 111:8242–47.

Montagnini, F., B. Haines, and W. T. Swank. 1991. Soil-solution chemistry in black locust, pine/mixed-hardwoods, and oak/hickory forest stands in the southern Appalachians, USA. *Forest Ecology and Management* 40 (3–4):199–208. doi:10.1016/0378-1127(91)90039-X.

Nägali, A., and F. Schanz. 1991. The influence of extracellular algal products on the surface tension of water. *International Review of Hydrobiology* 76 (1):89–103. doi:10.1002/iroh.19910760110.

Noran, R., U. Shani, and I. Lin. 1996. The effect of irrigation with magnetically treated water on the translocation of minerals in the soil. *Magnetic and Electrical Separation* 7 (2):109–22. doi:10.1155/1996/46596.

North, S. 2012. Waterlogging, anoxia and wheat growth in surface irrigated soils. In *Capturing Opportunities and Overcoming Obstacles in Australian Agronomy: Proceedings of 16th Australian Agronomy Conference*, October 14-18, Armidale, New South Wales, Australia, (ed.) I. Yunusa. Australian Society of Agronomy Inc.

Nunes, J. M., A. López-Piñeiro, A. Albarrán, A. Muñoz, and J. Coelho. 2007. Changes in selected soil properties caused by 30 years of continuous irrigation under Mediterranean conditions. *Geoderma* 139 (3–4):321–28. doi:10.1016/j.geoderma.2007.02.010.

Pelofsky, A. H. 1966. Surface tension-viscosity relation for liquids. *Journal of Chemical Engineering Data* 11 (3):394–97. doi:10.1021/je60030a031.

SAS Institute Inc. 2012. *SAS online documentation, version 9.4 [CD]*. Cary, NC: SAS Institute, Inc. Retrieved from https://documentation.sas.com/?cdcId=pgmsascdc&cdcVersion=9.4_3.5&docsetId=allprodsproc&docsetTarget=procedures.htm&locale=en

Schwab, G. O., D. D. Fangmeier, and W. J. Elliot. 1996. *Soil and water management systems*. New York: John Wiley & Sons.

Segeren, A. G., and T. J. Trout. 1991. Hydraulic resistance of soil surface seals in irrigated furrows. *Soil Science Society of America Journal* 55 (3):640–46. doi:10.2136/sssaj1991.03615995005500030002x.

Shi, R., and H. Tanaka. 2020. Direct evidence in the scattering function for the coexistence of two types of local structures in liquid water. *Journal of the American Chemical Society* 142 (6):2868–75. doi:10.1021/jacs.9b11211.

Sposito, G. 1984. *The surface chemistry of soils*. New York: Oxford University Press.

Srivastava, M. S., and E. M. Carter. 1983. *An introduction to applied multivariate statistics*. New York: North Holland.

Surendran, U., O. Sandeep., and E. J. Joseph. 2016. The impacts of magnetic treatment of irrigation water on plan, water, and soil characteristics. *Agricultural Water Management* 178:21–29. doi:10.1016/j.agwat.2016.08.016.

Toledo, E. J. L., R. Custodio, T. C. Ramalho, M. E. G. Porto, and Z. M. Magriotis. 2009. Electrical field effects on dipole moment, structure and energetic of $(H_2O)_n$ $(2 \le n \le 15)$ cluster. *Journal of Molecular Structure: THEOCHEM* 915 (1–3):170–77. doi:10.1016/j.theochem.2009.08.035.

Vennard, J. K., and R. L. Street. 1982. *Elementary fluid mechanics*. New York: John Wiley & Sons.

Waring, R. H., and S. W. Running. 2007. *Forest ecosystems analysis at multiple scales*. Burlington, MA, USA: Elsevier Academic Press.

Wiklander, L. 1974. Leaching of plant nutrients in soils: General principles. *Acta Agricultural Scandinavica* 24 (4):349–56. doi:10.1080/00015127409434213.

Does Turbulent-Flow Conditioning of Irrigation Water Influence Soil Chemical Processes: I. Laboratory Results

Rodrick D. Lentz*[1]

[1] USDA-ARS Northwest Irrigation and Soils Research Laboratory, 3793 N 3600 E, Kimberly, ID 83341;

*Corresponding Author. phone: (208) 421-7607; email: rk_lentz@netzero.com

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Supplemental Information (8 pages):

Tables S1 to S3

Figure S1

Table S1. Average soil property values of eroded Portneuf silt loam.

Material	Sand[†]	Silt[†]	Clay[†]	EC[‡]	CEC[‡]	pH[‡]	$CaCO_3$[§]	OC[§]	C[¶]	N[¶]	C:N
	----------	g kg^{-1}	----------	dS m^{-1}	mol_c kg^{-1}		%	-----------	g kg^{-1}	-----------	
Soil	220	600	180	0.45	0.21	8.0	28	5.8	34.3	0.7	49.0

[†] Particle size analysis: hydrometer method applied after removal of organic matter.

[‡] Electrical conductivity (EC) and pH determined on saturated extract; CEC = cation exchange capacity.

[§] Calcium carbonate equivalent ($CaCO_3$) was determined using a pressure-calcimeter (Sherrod, L.A., G. Dunn, G.A. Peterson, and R.L. Kolberg. 2002. Inorganic carbon analysis by modified pressure-calcimeter method. *Soil Science Society of America Journal* 66:299–305.). Organic carbon (OC) was determined by dry combustion after pretreatment to remove inorganic carbon (Shimadzu Total Carbon Analyzer).

[¶] Soil total carbon (TC) and total N were determined on a freeze-dried sample with a Thermo-Finnigan FlashEA1112 CN analyzer (CE Elantech Inc., Lakewood, NJ)

Table S2. Experiment 1. Effect of turbulent conditioning on water chemistry and properties (*n*=5). Included are the *p*-values testing treatment effects.

	Water Type†				
	Tap		CTap		
Nutrient / element	mean	SD	mean	SD	P-value
DIC (mg L^{-1})	61.4	7.5	61.7	7.5	ns
DOC (mg L^{-1})	4.16	3.8	3.82	3.5	ns
NH_4-N (mg L^{-1})	0.03	0.02	0.03	0.02	ns
NO_3-N (mg L^{-1})	4.53	0.27	4.54	0.34	ns
Ca (mg L^{-1})	50.6	3.7	50.6	3.7	ns
Na (mg L^{-1})	59.7	4.9	59.8	9.0	ns
Mg (mg L^{-1})	28.3	2.2	28.2	1.9	ns
K (mg L^{-1})	4.89	0.3	4.92	0.5	ns
Fe (mg L^{-1})	0.00 ‡	-	0.00	-	ns
Zn (mg L^{-1})	0.00 ‡	-	0.00	-	ns
Mn (mg L^{-1})	0.00 ‡	-	0.00	-	ns
Al (mg L^{-1})	0.00 ‡	-	0.00	-	ns
Cl (mg L^{-1})	14.5	2.8	14.6	2.8	ns
S (mg L^{-1})	21.0	1.1	20.9	0.4	ns
P (mg L^{-1})	0.11	0.11	0.16	0.24	ns
pH	7.23	0.23	7.21	0.19	ns
EC (dS m^{-1})	0.89	0.07	0.87	0.09	ns

*, $P \leq 0.05$ **, $P \leq 0.01$ ***, $P \leq 0.001$ ns, non significant

† Tap = tap water; CTap = conditioned tap water

‡ Micronutrient concentrations were below analytical detection limits.

Table S3. Experiment 2. Effect of turbulent conditioning on water chemistry of extractant water and extracted filtrate after water and soil were mixed 1-h on a reciprocal shaker (*n*=4). The *P*-values test treatment effects.

	------------ Input Water ------------			--------- Extracted Water ---------		
	Water Type			Water Type		
Nutrient/element	Tap	CTap	P-value	Tap	CTap	P-value
DIC (mg L^{-1})	62.4	61.9	ns	60.9	61.0	ns
DOC (mg L^{-1})	8.6	4.4	ns	49.6	47.0	ns
NH_4-N (mg L^{-1})	0.02	0.02	ns	0.61	0.64	ns
NO_3-N (mg L^{-1})	4.69	4.69	ns	17.7	17.8	ns
Ca (mg L^{-1})	56.0	56.2	ns	81.0	80.1	ns
Na (mg L^{-1})	64.8	64.9	ns	68.0	66.8	ns
Mg (mg L^{-1})	31.8	31.7	ns	39.6	39.6	ns
K (mg L^{-1})	5.4	5.4	ns	62.7	62.0	ns
Fe (mg L^{-1})	0.003	0.002	ns	0.038	0.031	ns
Zn (mg L^{-1})	0.00‡	0.00	ns	0.00	0.00	ns
Mn (mg L^{-1})	0.01	0.00	ns	0.01	0.01	ns
Al (mg L^{-1})	0.00‡	0.00	ns	0.04	0.04	ns
Cl (mg L^{-1})	14.3	14.4	ns	41.6	41.5	ns
S (mg L^{-1})	21.8	21.8	ns	35.5	35.2	ns
P (mg L^{-1})	0.20	0.20	ns	1.82	1.81	ns
pH	7.19	7.19	ns	7.65	7.60	ns
EC (dS m^{-1})	0.87	0.87	ns	1.04	1.04	ns

*, $P \leq 0.05$ **, $P \leq 0.01$ ***, $P \leq 0.001$ ns, non significant

† Tap = tap water; CTap = conditioned tap water

‡ Micronutrient concentrations for some replicates were below analytical detection limits.

FIG. S1

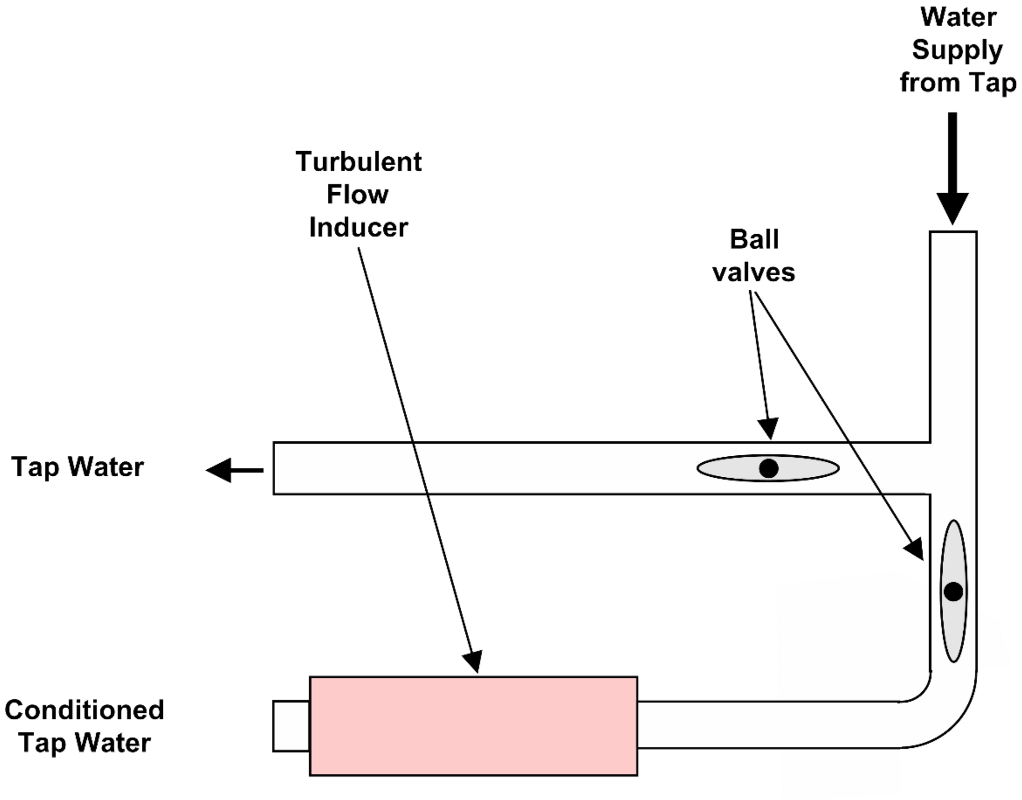

Fig. S1. The design of plumbing arrangement used to create alternating supplies of tap and conditioned tap water from the laboratory water system.