

Article

Uptake of Sulfate from Ambient Water by Freshwater Animals

Michael B. Griffith ^{1,2,*}, James M. Lazorchak ^{2,3} and Herman Haring ⁴

¹ U.S. Environmental Protection Agency, Office of Research and Development, National Center for Environmental Assessment, Cincinnati, OH 45268, USA

² U.S. Environmental Protection Agency, Office of Research and Development, Center for Environmental Measurement and Modeling, Cincinnati, OH 45268, USA; lazorchak.jim@epa.gov

³ U.S. Environmental Protection Agency, Office of Research and Development, National Exposure Research Laboratory, Cincinnati, OH 45268, USA

⁴ Pegasus Technical Services, Inc., Cincinnati, OH 45268, USA; herman.haring@hotmail.com

* Correspondence: griffith.michael@epa.gov

Received: 3 April 2020; Accepted: 20 May 2020; Published: 23 May 2020

Abstract: To better understand how the sulfate (SO_4^{2-}) anion may contribute to the adverse effects associated with elevated ionic strength or salinity in freshwaters, we measured the uptake and efflux of SO_4^{2-} in four freshwater species: the fathead minnow (*Pimephales promelas*, Teleostei: Cyprinidae), paper pondshell (*Utterbackia imbecillis*, Bivalvia: Unionidae), red swamp crayfish (*Procambarus clarkii*, Crustacea: Cambaridae), and two-lined mayfly (*Hexagenia bilineata*, Insecta: Ephemeraidae). Using $\delta(^{34}\text{S}/^{32}\text{S})$ stable isotope ratios and the concentrations of S and SO_4^{2-} , we measured the SO_4^{2-} influx rate (J_{in}), net flux (J_{net}), and efflux rate (J_{out}) during a 24 h exposure period. For all four species, the means of J_{in} for SO_4^{2-} were positive, and J_{in} was significantly greater than 0 at both target SO_4^{2-} concentrations in the fish and mollusk and at the lower SO_4^{2-} concentration in the crayfish. The means of J_{out} and J_{net} were much more variable than those for J_{in} , but several species by target SO_4^{2-} concentration combinations for J_{out} and J_{net} , were negative, which suggests the net excretion of SO_4^{2-} by the animals. The results of our experiments suggest a greater regulation of SO_4^{2-} in freshwater animals than has been previously reported.

Keywords: sulfate; freshwater; uptake; efflux; fish; invertebrates

1. Introduction

Water quality benchmarks were recently developed for elevated total ion concentrations in freshwaters using specific conductance as a measurement endpoint to protect aquatic life [1,2]. However, there is still uncertainty about how different ions contribute to the adverse effects associated with elevated total ionic strength or salinity on freshwater biota, and some studies have suggested a more traditional approach where the concentrations of specific anions should be the targets of chemical monitoring and ambient water quality criteria [3–6]. The predominant form of dissolved sulfur (S) in water is the anion, sulfate (SO_4^{2-}), which can be especially elevated in waters affected by mining. Mining exposes sulfide-rich minerals, such as pyrite associated with coal mining and other metal sulfides associated with hard rock metal mining [7–10]. Under oxic conditions, these sulfides are rapidly transformed into SO_4^{2-} .

Several studies have recently attempted to assess the ecotoxicity of SO_4^{2-} with standard bioassays that have exclusively used Na_2SO_4 [11–14]. The objective of at least some of these studies is the compilation of sufficient bioassay data for a species sensitivity distribution to develop an ambient water criterion for SO_4^{2-} . These studies attribute many of the observed adverse effects to SO_4^{2-} . This assumes that any effects associated with the concurrently elevated concentrations of Na^+ are minor,

even though the uptake of Na^+ across epithelial membranes is well known [15–17]. Additionally, the uptake of SO_4^{2-} across external epithelial membranes, such as gills, occurs and has an ionoregulatory or osmoregulatory adverse effect on these animals. However, because the transport physiology of SO_4^{2-} in freshwater animals is relatively unstudied, the validity of the second assumption is unknown. Other studies have begun to study the interactions between different anion and cation combinations [18–20].

To support decisions relating to the potential for adverse effects associated with individual major ions, Na^+ , K^+ , Ca^{2+} , Mg^{2+} , Cl^- , SO_4^{2-} , and HCO_3^- , we previously published a literature review on the ion physiology of freshwater species of four animal groups: teleost fish, crustaceans, aquatic insects, and mollusks [21]. While this review found extensive literature on many of these major ions at least for teleost fish, if not always for the freshwater invertebrates, it identified a data gap related to the ionoregulatory physiology of SO_4^{2-} . Limited data appear to suggest that SO_4^{2-} is relatively impermeant to the gill membranes of fish [22,23], crustaceans [24,25], or unionid mussels [26]. However, SO_4^{2-} -transporters are present in amphibian skin [27], which functions in ion uptake similarly to the gill membranes of fish, crustaceans, and mollusks or to anal papillae, chloride epithelia, or other epithelial surfaces in aquatic insects [21]. However, see the research on SO_4^{2-} uptake from the water that has been recently published on aquatic insects by Scheibener et al. [28] and Buchwalter et al. [29].

Like other major ions, SO_4^{2-} is present in the extracellular fluids (i.e., blood or hemolymph) of freshwater animals. Reported SO_4^{2-} concentrations include 0.76 ± 0.18 mmol/L ($n = 6$); 2.58 ± 0.06 ($n = 30$) and 2.60 ± 0.90 mmol/L ($n = 7$) in two species of *Anodonta* and zebra mussels (*Dreissena polymorpha*), respectively (Mollusca) [30–32]; 0.94 ± 0.26 for the spinycheek crayfish (*Orconectes limosus*) [33]; and 0.89 and 2.14 mmol/L for white sucker (*Catostomus commersoni*) and rainbow trout (*Oncorhynchus mykiss*), respectively [34]. A greater SO_4^{2-} concentration of 18.7 mmol/L was observed in freshwater Japanese eels (*Anguilla japonica*) [35], but the authors suggest this catadromous species balances greater SO_4^{2-} with less Cl^- in its blood.

Moreover, SO_4^{2-} is metabolically active. S is a component of the amino acids methionine and cysteine, which produce S-containing proteins, and a component of other biomolecules, such as sulfated glycosaminoglycans, which are generally ubiquitous in metazoans, including mollusks, crustaceans, insects, and fish [36–39]. In most organisms, the initial step in S assimilation is SO_4^{2-} activation to 3'-phosphoadenosine 5'-phosphosulfate (PAPS) [40–43].

Freshwater animals are generally hyperregulators that maintain greater ion concentrations in their blood or hemolymph than are found in surrounding freshwaters [44]. As the external medium is hypoosmotic or more dilute than body fluids, these species deal with the continuous diffusional loss of salts and the osmosis of water across their permeable membranes. Therefore, water balance is accomplished by the excretion of dilute waste fluids by their renal systems. Salt concentrations are maintained by the function of various ion transporting proteins in epithelial membranes, such as in the gills, gastrointestinal system, or renal system, that allow the active transport of ions against concentration gradients (i.e., the absorption of ions from the surrounding water or food or the reabsorption of ions from waste fluids, such as urine). Furthermore, most freshwater species, unlike saltwater species, limit their drinking of water, thereby limiting the absorption of water through the gastrointestinal system and dilution of the hemolymph. However, increased water concentrations of some ions, such as SO_4^{2-} , change concentration gradients across the epithelial membranes involved in ionoregulation, such as the gills. This may change SO_4^{2-} influx across these membranes, increase blood or hemolymph SO_4^{2-} concentrations, and have osmoregulatory or other adverse effects. However, it is also possible that these epithelial membranes could be impermeant to SO_4^{2-} , and none of the above effects may occur. To test whether SO_4^{2-} can move across epithelial membranes, we conducted laboratory experiments with a fish, a crustacean, a mollusk, and a mayfly. These experiments used protocols similar to traditional toxicity tests in that the organisms were exposed to reconstituted water with elevated SO_4^{2-} concentrations. However, the concentrations were not expected to have overtly adverse effects, such as mortality. Moreover, the reconstituted water was

made, in part, with enriched $\text{Na}_2[^{34}\text{S}]\text{O}_4$ to elevate its $\delta(^{34}\text{S}/^{32}\text{S})$. After exposure, the whole body stable isotope ratios of S were measured to assess whether the ^{34}S associated with animal tissues increased.

This study was designed to fill a data gap by conducting laboratory experiments with species from four freshwater animal groups (crustaceans, fish, unionid mussels, and aquatic insects) to measure SO_4^{2-} uptake from ambient waters and the effect of ambient SO_4^{2-} concentrations on SO_4^{2-} uptake. Significant SO_4^{2-} uptake from the water into an animal would show that the epithelial membranes are permeant to SO_4^{2-} , likely via an ion-specific transporter. This SO_4^{2-} uptake would affect internal SO_4^{2-} concentrations, would play a direct role in ionoregulation by the animal, and could have adverse effects if elevated in freshwaters.

2. Materials and Methods

To test whether SO_4^{2-} uptake is similar or differs among different major taxa groups of freshwater animals, we conducted parallel experiments using a representative species in each of four taxa groups. The ion transport physiology of these species is unlikely to change with the aquatic developmental stage [21]. Therefore, juvenile fish and crayfish, adult unionid mussels, and later instar mayfly nymphs were used in the experiments. The exposures for each of the four species was conducted during a single 24 h period, but the experiments were conducted at different times between September 2017 and April 2019.

2.1. Test Animals

Although we considered, originally, using model species (e.g., Cladocera and Chironomidae), often used by toxicity studies, our methods required larger individuals to provide sufficient biomass for stable isotope analysis. We selected the fathead minnow (*Pimephales promelas* Rafinesque, 1820) which is commonly used as a model for a teleost fish. Less conventional test species included a mollusk, the paper pondshell (*Utterbackia imbecillis* (Say, 1829)); a crustacean, the red swamp crayfish (*Procambarus clarkii* (Girard, 1852)); and an aquatic insect, the two-lined mayfly (*Hexagenia bilineata* (Say, 1824)).

We used fathead minnows from laboratory colonies usually cultured and maintained for toxicity testing according to [45,46]. We fed them live *Artemia* nauplii twice a day at a rate of 1 mL per 20 L tank per day-of-age per feeding with a nauplii suspension of 15 mL of brine shrimp cysts (Brine Shrimp Direct, Ogden, UT, USA) incubated for 24 h at 28 °C in aerated Labline water with 25 mL NaCl added.

We purchased red swamp crayfish from Carolina Biological Supply Co., Burlington, NC, USA. The crayfish were placed in a tank with about 175 L of water aerated with air stones. Lengths of polyvinyl chloride pipe cut in half lengthwise were placed in the aquaria to provide cover for the crayfish and reduce aggression. The crayfish were fed thawed adult *Artemia* ad libitum daily.

We obtained the paper pondshells from the Kentucky Department of Fish and Wildlife Resources' Center for Mollusk Conservation (Frankfort, KY, USA). The mussels were held in aquaria, with 28 individuals per aquarium, where the water was aerated by an air stone. The mollusks were fed 20 mL of FFAY, an internally made mixture of fish flake food (Tetramin®, Tetra, Blacksburg, VA, USA), alfalfa (from capsule; Nature's Way, Fargo, ND, USA), and yeast (Flieschmann's, Oakbrook Terrace, IL, USA); and 15 mL of an algal culture of flagellated algae and diatoms (Shellfish Diet 1800®, Reed Mariculture, Campbell, CA, USA) and 15 mL of alfalfa per tank daily.

We purchased the two-lined mayfly from The Reel Thing Live Bait, Green Bay, WI, USA. The mayfly nymphs were held in aquaria, where the water was aerated by an air stone, and were fed ground cereal grain flake food (Cerophyll®, Ward's Natural Science Establishment, Inc., Rochester, NY, USA).

Before their use in experiments, we held the fish and invertebrates in dechlorinated and hardness-adjusted municipal tap water (mean ionic composition in mmol L⁻¹: 1.04 [Na⁺], 0.05 [K⁺], ~0.25–0.55 [Ca²⁺], 0.43 [Mg²⁺], ≤ 0.01 [Cl⁻], and 0.93 [SO₄²⁻]; pH: 7.2–8.1; total organic carbon (TOC): ~0.08 mg C L⁻¹; and hardness: ~150–180 mg L⁻¹ as CaCO₃). All animals, except the two-lined mayflies,

were maintained at a constant temperature of 25 ± 1 °C with a 16:8 h light to dark photoperiod. The two-lined mayflies were maintained at a constant temperature of 15 ± 1 °C.

For at least 24 h before the individual experiments, the animals were acclimated to a modified moderately hard reconstituted water (MMHRW) similar to the R-MHRW of Smith et al. [47] generated by the addition of reagent-grade salts to deionized water produced by a Millipore Super-Q Plus water purification system and bubbled with CO₂ to dissolve the CaCO₃, particularly using Na₂SO₄ (Table 1). During the 24 h acclimation and test phases, the animals were not fed, while the holding water temperatures were maintained.

Table 1. Concentrations of salts in the modified moderately hard reconstituted water (MMHRW) used in the experiment along with the resulting target mmol L⁻¹ of the major ions, along with hardness and the molar [Na⁺]/[K⁺] ratios. Only the concentrations of Na⁺ and SO₄²⁻ were increased in the MMHRW.

Water	Salt	mg L ⁻¹	Ions	mmol L ⁻¹
Acclimation	CaCO ₃	71.0	Na ⁺	0.54
	NaHCO ₃	4.0	K ⁺	0.05
	MgCl ₂ ·6H ₂ O	59.4	Ca ²⁺	0.71
	KCl	3.5	Mg ²⁺	0.29
	Na ₂ SO ₄	35.0	HCO ₃ ⁻	1.47
			Cl ⁻	0.34
			SO ₄ ²⁻	0.25
			Hardness (mg/L, CaCO ₄)	100.2
0.49 mmol L ⁻¹ SO ₄ ²⁻			Molar [Na ⁺]/[K ⁺]	11.5
	Na ₂ SO ₄	70.0	Na ⁺	1.03
			SO ₄ ²⁻	0.49
			Hardness (mg/L, CaCO ₄)	100.2
1.23 mmol L ⁻¹ SO ₄ ²⁻			Molar [Na ⁺]/[K ⁺]	22.0
	Na ₂ SO ₄	175.0	Na ⁺	2.51
			SO ₄ ²⁻	1.23
			Hardness (mg L ⁻¹ , CaCO ₄)	100.2
			[Na ⁺]/[K ⁺]	53.5

MMHRW = modified moderately hard reconstituted water

2.2. Test Water

Upon the initiation of the experiment, the animals were exposed to two concentrations of SO₄²⁻, with the MMHRW with Na₂SO₄ added to increase by 2× (i.e., 0.49 mmol L⁻¹) or 5× (1.23 mmol L⁻¹) the SO₄²⁻ concentrations to test whether differing water SO₄²⁻ concentrations influenced uptake (Table 1). This addition also increased Na⁺ concentrations to 1.03 mmol L⁻¹ and 2.51 mmol L⁻¹, respectively. None of these concentrations are near the concentrations that have been observed to have acute adverse effects on freshwater animals [6,11,12,48]. Moreover, the Na⁺/K⁺ molar ratios were 22.0 and 53.5, respectively, which are within the range where alterations of this ratio have not been observed to have osmoregulatory effects [49,50].

To observe influx rates, test water made with unenriched reagent grade Na₂SO₄ was mixed with the same concentration test water made with 90% atom enriched Na₂[³⁴S]O₄ (Sigma-Aldrich, Miamisburg, OH, USA) at a ratio of 939 parts of reagent grade test water to 61 parts of 90% atom enriched test water. A test water made with only 90% atom enriched Na₂[³⁴S]O₄ could not be used without dilution to reduce the enrichment of the ³⁴S. Too strong of a signal from ³⁴S when the samples are analyzed in the mass spectrometer can overload the detectors and cause falsely elevated concentration readings in subsequent samples (R. Venkatapathy, personal communication).

2.3. Sampling Methods

2.3.1. Measurements of Animals and Water

Measurements were made on organisms placed in containers with aeration, containing 200 mL, 12 L, 7 L, and 150 mL of the waters for the minnow, unionid mollusk, crayfish, and mayfly, respectively. The volumes were chosen based on the mass loading limits for the animals in static tests [45]. The two-lined mayflies were supplied with short lengths (~38 mm) of 9.5 mm inner-diameter vinyl tubing as artificial burrows [51]. In all four species, the mass of the animal (i.e., ≥ 10 mg dry mass) was sufficient for chemical analysis, permitting us to measure each individual.

Subsamples of the test waters were taken to measure the SO_4^{2-} concentrations and $\delta(^{34}\text{S}/^{32}\text{S})$ for each exposure at 0 h, and a water sample was taken from each exposure container to measure the SO_4^{2-} concentrations after the 24 h exposures. At least 10 extra individuals of each species were sacrificed at 0 h to measure initial whole-body S concentrations and $\delta(^{34}\text{S}/^{32}\text{S})$. Measurements from 25 separate replicates of each SO_4^{2-} concentration were collected for each test species. From every exposure, replicate whole-body samples of each test species were taken at the end of the exposure to the enriched stable isotope water and used to measure whole-body S concentrations and $\delta(^{34}\text{S}/^{32}\text{S})$. However, because there was some mortality in the two-lined mayfly experiment, the numbers of replicates were 17 and 22 for the 0.49 and 1.25 mmol L^{-1} SO_4^{2-} exposures, respectively. Moreover, an error in the initial water SO_4^{2-} analysis in the mayfly experiment reduced the number of valid measurements of the initial 0.49 mmol L^{-1} water SO_4^{2-} concentration to 1, precluding valid means of J_{out} and J_{net} for the 0.49 mmol L^{-1} SO_4^{2-} exposure.

At the end of each exposure, the fish, crayfish, or mayfly nymph individuals were removed from the containers, rinsed in deionized water to remove any stable isotope label from the surface, and blotted dry on filter paper. For the unionid mussel, the soft tissue was cut from the shell. The fish, mussels (soft tissue only), and mayfly nymphs were dried overnight at 90 °C, whereas the crayfish were freeze-dried for 14 days to weaken their exoskeletons. The animals were then weighed, homogenized, and powdered to 100–200 μm with a mortar and pestle, stored in vials, and analyzed for total S and $\delta(^{34}\text{S}/^{32}\text{S})$ [52].

2.3.2. Chemical Analysis of Test Water and Animals

The total concentrations of SO_4^{2-} in the test waters were measured with ion chromatography (EPA Method 300.0) [53]. For the stable isotope analysis of SO_4^{2-} in the initial test waters, we precipitated the dissolved SO_4^{2-} in subsamples of the water placed in the test chambers as barium sulfate (BaSO_4) following Révész et al. [54].

The total S concentration of the dried animal tissues was measured using an elemental analyzer. The molar ratios of $^{34}\text{S}/^{32}\text{S}$, reported as the deviation of this ratio from the international standard, Canon Diablo Troilite, or $\delta(^{34}\text{S}/^{32}\text{S})$ [55], were measured in both the BaSO_4 precipitates and dried animal tissues with an elemental analyzer connected to a continuous-flow 20-20 gas source stable isotope ratio mass spectrometer [52,54]. For ^{34}S analyses, the sample was placed in a tin capsule with vanadium dioxide for combustion, the combustion reactor was held at 1080 °C, and the reaction tube contained tungsten oxide on alumina as an oxidative catalyst and copper metal to remove excess O_2 subsequent to combustion. The S in the sample was converted to SO_2 and, along with N_2 and CO_2 , was passed through two H_2O traps. The purified gases were then separated in a 30 cm, 0.5" OD, QS GC column held at 45 °C and passed into the mass spectrometer— N_2 and CO_2 first, and then SO_2 . Approximately one-third of the SO_2 was cracked to SO in the source, allowing ^{34}S to be measured by continuously monitoring masses 48, 49, and 50. The mass peaks were plotted, the area under each mass peak was determined, and the isotope ratios were calculated. These ratios were referenced to ratios determined on in-house reference materials analyzed in the same analytical run. The raw ratio data were corrected for drift over the course of the run along with blank/linearity effects, and if present, then normalized to the international standards. Analytical precisions, based on the replicate analyses of international reference materials, were $\pm 0.3\text{‰}$ for $\delta^{34}\text{S}$.

2.3.3. Compartmental Analysis to Calculate the Influx and Efflux of Sulfate

The SO_4^{2-} , total S, and $\delta^{34}\text{S}$ ratio data were used in a compartmental analysis of a single pool system for using stable isotope tracer data [56,57] modified from models using radioisotope data for ion uptake by fish and crayfish [58–60]. Compartmental analysis models the movement of a solute between two compartments based on diffusion and mass conservation. In this system, we are measuring the movement of SO_4^{2-} between the surrounding water and the animal across semipermeable epithelial cell membranes that may be facilitated by the presence of SO_4^{2-} -specific transporter proteins. This is because the SO_4^{2-} in the test water can be traced with the artificially elevated levels of ^{34}S by the SO_4^{2-} -influx rate (J_{in}). However, because only the change in the SO_4^{2-} concentration in the test waters was used to measure the net SO_4^{2-} -flux rate (J_{net}), the SO_4^{2-} -efflux rate (J_{out}) may include S from sources other than the test water, such as food.

2.3.4. Calculations

J_{net} was measured as the change in the water SO_4^{2-} concentration during the exposure period ($t = 1$ day):

$$J_{\text{net}} = \frac{[\text{SO}_4^{2-}]_0 \times V_0 - [\text{SO}_4^{2-}]_t \times V_t}{M \times t} \quad (1)$$

where $[\text{SO}_4^{2-}]_0$ and $[\text{SO}_4^{2-}]_t$ are the concentrations of SO_4^{2-} in the water ($\mu\text{mol L}^{-1}$) at the beginning and end of the exposure period, respectively; V is the volume of the water in the chamber (L) measured at $t = 0$ and $t \approx 24$ h to account for evaporation; M is the mass (g) of the animal placed into the container; and t is the length of the exposure period (days).

J_{in} was measured as the changes in the fractional molar abundance of ^{34}S and total S concentration in the animal during the exposure interval relative to the initial fractional molar abundance of ^{34}S in the test waters:

$$J_{\text{in}} = \frac{[X(^{34}\text{S})]_{\text{int}(t)} \times [S]_{\text{int}(t)} - [X(^{34}\text{S})]_{\text{int}(0)} \times [S]_{\text{int}(0)}}{[X(^{34}\text{S})]_{\text{bath}} \times t} \quad (2)$$

where $X(^{34}\text{S})_{\text{int}(0)}$ is the initial fractional molar abundance of ^{34}S in the animal, $[S]_{\text{int}(0)}$ is the initial concentration of S in the animal ($\mu\text{mol g}^{-1}$), $X(^{34}\text{S})_{\text{int}(t)}$ is the fractional molar abundance of ^{34}S at the end of the exposure, $[S]_{\text{int}(t)}$ is the concentration of S in the animal at the end of the exposure ($\mu\text{mol g}^{-1}$), $X(^{34}\text{S})_{\text{bath}}$ is the fractional molar abundance of ^{34}S in the test waters, and t is the length of the exposure period (day).

The fractional molar abundance of ^{34}S or $X(^{34}\text{S})$ for a sample is calculated from the molar ratio of ^{34}S to ^{32}S or $R(^{34}\text{S}/^{32}\text{S})$ for the sample by:

$$X(^{34}\text{S}) = \frac{R(^{34}\text{S}/^{32}\text{S})}{1 + R(^{34}\text{S}/^{32}\text{S})} \quad (3)$$

and $R(^{34}\text{S}/^{32}\text{S})$ is calculated from the reported $\delta(^{34}\text{S}/^{32}\text{S})$ by:

$$R(^{34}\text{S}/^{32}\text{S}) = \frac{\delta(^{34}\text{S}/^{32}\text{S}) \times N(^{34}\text{S})_{\text{std}}/N(^{32}\text{S})_{\text{std}}}{1000} + N(^{34}\text{S})_{\text{std}}/N(^{32}\text{S})_{\text{std}} \quad (4)$$

where $N(^{34}\text{S})_{\text{std}}/N(^{32}\text{S})_{\text{std}}$ is the molar ratio of the heavy stable isotope in the standard material, Canyon Diablo Troilite, which by convention is assigned a $N(^{34}\text{S})/N(^{32}\text{S})$ of 0.045005 [61]. The values are divided by 1000, because $\delta(^{34}\text{S}/^{32}\text{S})$ is reported in parts per mille relative to the standard material.

J_{out} is calculated as the difference between J_{net} and J_{in} [58]:

$$J_{\text{out}} = J_{\text{net}} - J_{\text{in}} \quad (5)$$

2.3.5. Statistical Analysis

As the measurements of SO_4^{2-} and $\delta(^{34}\text{S}/^{32}\text{S})$ in the water and in animals at the beginning of the exposures were made on and summarized for replicate subsamples, the variation associated with these measurements was pooled as appropriate with the variation of the calculated variables, J_{in} , J_{out} , and J_{net} . Then, the calculated variables for each species were tested to determine whether each variable was significantly different from 0 using a t-test (PROC TTEST, SAS Institute, Cary, NC, USA). Because six variable-by-concentration combinations were tested for each species, a Bonferroni adjustment of $p = 0.0083$ was used.

3. Results

The measured SO_4^{2-} concentrations in the artificial water used with the different species were variable compared to the target concentrations (Table 2). The measured $\delta(^{34}\text{S}/^{32}\text{S})$ for the artificial waters (Table 2) were more than 100 times the initial measured $\delta(^{34}\text{S}/^{32}\text{S})$ of the animal tissues, which were $+11.386 \pm 0.090$, -1.420 ± 0.910 , -2.304 ± 0.987 , and -4.617 ± 0.530 for the fathead minnows, paper pondshells, red swamp crayfish, and two-lined mayflies, respectively. The summary statistics for all the variables used in the compartmental analyses may be found in Table S1.

Table 2. Measured initial characteristics of SO_4^{2-} in the test water for each species exposure. The column headings are the nominal concentrations of SO_4^{2-} . The values are the sample mean $\pm$ 1 standard error. $[\text{SO}_4^{2-}]$ (mmol L^{-1}) is the concentration of SO_4^{2-} , and $\delta(^{34}\text{S}/^{32}\text{S})$ (‰) is molar ratio of $^{34}\text{S}/^{32}\text{S}$ of the SO_4^{2-} .

Variable	Species	0.49 mmol L^{-1}		1.23 mmol L^{-1}	
		n	Value	n	Value
$[\text{SO}_4^{2-}]$ (mmol L^{-1})	Fathead minnow	5	0.52 ± 0.03	5	1.67 ± 0.03
	Paper pondshell	5	0.35 ± 0.01	5	0.98 ± 0.06
	Red swamp crayfish	10	0.45 ± 0.01	10	1.15 ± 0.01
	Two-lined mayfly	1	0.48	3	1.19 ± 0.04
$\delta(^{34}\text{S}/^{32}\text{S})$ (‰)	Fathead minnow	5	$+1377.6 \pm 1.3$	5	$+1433.9 \pm 0.8$
	Paper pondshell	5	$+1432.7 \pm 34.1$	5	$+1452.6 \pm 0.5$
	Red swamp crayfish	5	$+1475.6 \pm 2.8$	5	$+1461.3 \pm 1.0$
	Two-lined mayfly	5	$+1411.6 \pm 3.0$	5	$+1365.7 \pm 4.4$

The means of J_{in} for SO_4^{2-} were positive for all the species and ranged from 2.14 to 13.32 $\mu\text{mol g}^{-1} \text{ day}^{-1}$ among the species and two nominal sulfate concentrations (Figure 1). The J_{in} in 5 of 50, 12 of 50, 13 of 50, and 8 of 39 individual exposures of the fish, mollusk, crayfish, and mayfly were negative, and there were large confidence bounds around the means (i.e., the coefficient of variation ranges from 0.54 to 3.63). In part, notable variance was added to the means of J_{in} because of unexpected variation in the measurements of the initial animal S concentrations (Table 3), but J_{in} was significantly greater than 0 at both target SO_4^{2-} concentrations in the fish and mollusk and at the lower SO_4^{2-} concentration (i.e., 0.49 mmol L^{-1}) in the crayfish (Table 4). Additionally, J_{in} increased between the two SO_4^{2-} concentrations in the fish and mollusk (Figure 1), although the increase was statistically significant only for the fish ($df = 48$, $t = 2.70$, $p = 0.009$) and the mollusk ($df = 48$, $t = 1.13$, $p = 0.20$).

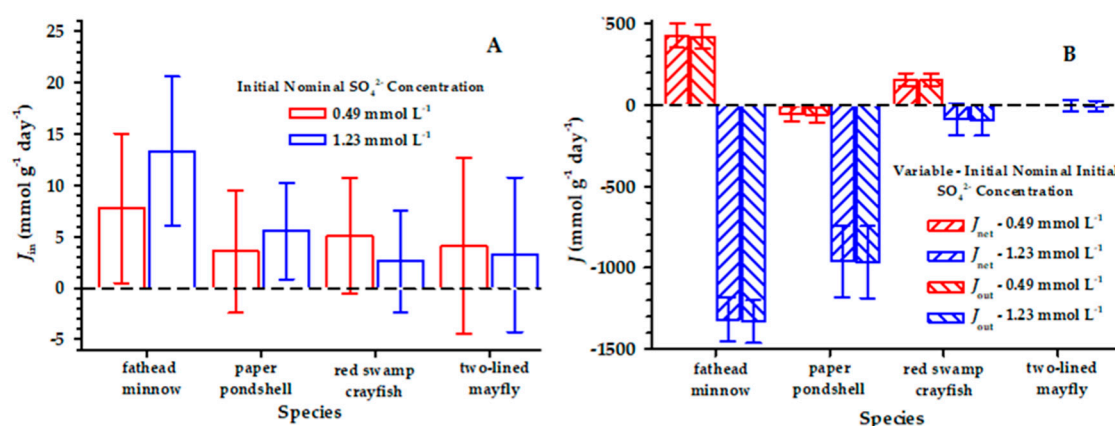


Figure 1. Mean SO_4^{2-} influx (J_{in}) (A), efflux (J_{out}), and net flux (J_{net}) (B) ($\mu\text{mol g}^{-1} \text{ day}^{-1}$) for each animal species—the fathead minnow, paper pondshell, red swamp crayfish, and two-lined mayfly—at the two target SO_4^{2-} concentrations of 0.49 mmol L⁻¹ and 175 mmol L⁻¹. The error bars represent ± 1 standard error. Because of some mortality occurring in the mayfly experiment, the numbers of replicates were 17 and 22 for the 0.49- and 1.25-mmol L⁻¹ SO_4^{2-} exposures, respectively. Moreover, an error in the initial water SO_4^{2-} analysis in the mayfly experiment reduced the number of valid measurements for the initial 0.49 mmol L⁻¹ water SO_4^{2-} -concentration to 1, precluding a valid mean of J_{out} and J_{net} for the 0.49 mmol L⁻¹ SO_4^{2-} exposure.

The means of J_{out} and J_{net} were much more variable but suggested a net excretion of SO_4^{2-} by the four species (Figure 1, Table 4). Part of this variation was the result of unexpected variation in the measurements of the initial water concentrations of SO_4^{2-} (Table 3).

Table 3. Proportion of variance in the J value means contributed by the variances of the mean values for component variables. The proportions of variance for other component variables were <0.001 , or means were not used in the calculations. $[S]_{int(0)}$ is the mean calculated initial S concentration ($\mu\text{mol g}^{-1}$) of each animal, and $[\text{SO}_4^{2-}]_0$ is the measured concentrations of SO_4^{2-} in the water ($\mu\text{mol L}^{-1}$) at the beginning of the exposure. J_{in} , J_{out} , and J_{net} are the influx rates, efflux rates, and net flux of SO_4^{2-} ($\mu\text{mol g}^{-1} \text{ day}^{-1}$), respectively, for each species.

Species	Target SO_4^{2-} Concentration	J value	Variable	Proportion of Variance
Fathead minnow	0.49 mmol L ⁻¹	J_{in}	$[S]_{int(0)}$	0.603
		J_{out}	$[\text{SO}_4^{2-}]_0$	0.089
			$[S]_{int(0)}$	0.015
		J_{net}	$[\text{SO}_4^{2-}]_0$	0.090
	1.23 mmol L ⁻¹	J_{in}	$[S]_{int(0)}$	0.584
		J_{out}	$[\text{SO}_4^{2-}]_0$	0.583
			$[S]_{int(0)}$	0.006
		J_{net}	$[\text{SO}_4^{2-}]_0$	0.058
Paper pondshell	0.49 mmol L ⁻¹	J_{in}	$[S]_{int(0)}$	0.172
		J_{out}	$[\text{SO}_4^{2-}]_0$	0.046
			$[S]_{int(0)}$	0.021
		J_{net}	$[\text{SO}_4^{2-}]_0$	0.047
	1.23 mmol L ⁻¹	J_{in}	$[S]_{int(0)}$	0.519
		J_{out}	$[\text{SO}_4^{2-}]_0$	0.059
			$[S]_{int(0)}$	0.001
		J_{net}	$[\text{SO}_4^{2-}]_0$	0.059
Red swamp crayfish	0.49 mmol L ⁻¹	J_{in}	$[S]_{int(0)}$	0.582
			$[\text{SO}_4^{2-}]_0$	0.028
		J_{out}	$[S]_{int(0)}$	0.012

Two-lined mayfly	1.23 mmol L ⁻¹	J_{net}	$[SO_4^{2-}]_0$	0.072
		J_{in}	$[S]_{int(0)}$	0.747
			$[SO_4^{2-}]_0$	0.002
	0.49 mmol L ⁻¹	J_{out}	$[S]_{int(0)}$	0.002
		J_{net}	$[SO_4^{2-}]_0$	0.005
		J_{in}	$[S]_{int(0)}$	0.890
	1.23 mmol L ⁻¹	J_{in}	$[S]_{int(0)}$	0.941
		J_{out}	$[SO_4^{2-}]_0$	0.346
			$[S]_{int(0)}$	0.084
		J_{net}	$[SO_4^{2-}]_0$	0.380

Table 4. T-value (df and p) for the test of the H_0 that each mean $J = 0$. mJ_{in} , mJ_{out} , and mJ_{net} are the mean influx rate, mean efflux rate, and mean net flux of SO_4^{2-} , respectively, for each species. Because of the multiple tests for each animal species, the Bonferroni adjustment of p is 0.0083. The t -values that indicate a mean J value statistically different from 0 are in bold.

Species	Target SO_4^{2-} Concentration	$H_0: mJ_{in} = 0$ t -Value (df, p)	$H_0: mJ_{out} = 0$ t -Value (df, p)	$H_0: mJ_{net} = 0$ t -Value (df, p)
Fathead minnow	0.49 mmol/L	5.32 (24, <0.0001)	27.88 (24, <0.0001)	28.60 (24, <0.0001)
	1.23 mmol/L	9.15 (24, <0.0001)	−49.38 (23, <0.0001)	−48.51 (23, <0.0001)
Paper pondshell	0.49 mmol/L	2.98 (24, 0.0066)	−6.38 (24, <0.0001)	−6.04 (24, <0.0001)
	1.23 mmol/L	5.91 (24, <0.0001)	−21.78 (24, <0.0001)	−21.74 (24, <0.0001)
Red swamp crayfish	0.49 mmol/L	4.50 (24, 0.0001)	19.26 (24, <0.0001)	20.34 (24, <0.0001)
	1.23 mmol/L	2.60 (24, 0.0155)	−4.80 (24, <0.0001)	−4.68 (24, <0.0001)
Two-lined mayfly	0.49 mmol/L	1.95 (17, 0.0680)		
	1.23 mmol/L	1.97 (21, 0.0623)	−0.33 (2, 0.77)	−0.16 (2, 0.89)

4. Discussion

Because we measured an increase in whole animal $R(^{34}S/^{32}S)$ in animals exposed to water where the added SO_4^{2-} was highly enriched with ^{34}S , J_{in} measured the uptake of SO_4^{2-} from the water. Presumably, the SO_4^{2-} moved through SO_4^{2-} -transporters on external epithelial membranes, such as the gills, chloride cells, or integument, because other ions commonly move through epithelial membranes via various intercellular pathways involving various ion transporters. Although our methods used whole animal assays and therefore did not definitively distinguish between external surfaces and internal tissues, the measured J_{in} , when expressed in the same units, are of a similar range of magnitude as the measurements of the uptake of other ions, including Cl^- anions, at similar water concentrations [62–65]. Even though our methods do not distinguish between ionocyte-mediated transport and paracellular transport, which has been described for other ions, paracellular transport does not generally occur against concentration gradients, and we expect that it would take longer than 24 h for the equilibration of the isotope between the test solution and the internal milieu without the aid of facilitated or active transport [66–69].

The larger J_{out} suggests that there is an internal pool of SO_4^{2-} supplied by sources in addition to uptake from the water, such as from food [70,71]. By measuring the change in the SO_4^{2-} concentration in the water, J_{out} and J_{net} measure all the effluxes of SO_4^{2-} between the animals and the water, including renal excretion.

A number of other studies have observed SO_4^{2-} transporters in aquatic animals, primarily associated with internal epithelial membranes. In teleost fish, two types of epithelial SO_4^{2-} transporters, a Na^+/SO_4^{2-} -cotransporter (NaS1, SLC13 family) and a SO_4^{2-} /anion-exchanger (Sat1, SLC26 family), have been identified in the proximal tubules of the kidneys that are primarily involved in SO_4^{2-} excretion and resorption [35,72,73]. The functional analysis of freshwater mollusks suggests a similar renal regulation of SO_4^{2-} [26,30]. In mosquito (*Aedes campestris*) larvae from saline lakes, transporters associated with the Malpighian tubules excrete SO_4^{2-} [74,75]. In marine Atlantic lobsters (*Homarus americanus*), SO_4^{2-} transporters associated with hepatopancreatic epithelia excrete SO_4^{2-} in exchange for either $C_2H_4^{2-}$ or Cl^- [76–79]. The Na^+/SO_4^{2-} -cotransporter, NaS1, was also detected in the

intestinal tissue of zebrafish (*Danio rerio*) but not gill tissues [72]. However, our experiments were not designed to identify the types of SO_4^{2-} transporters beyond their role in uptake from the ambient water.

The amino acid cysteine and S-containing proteins are synthesized in metazoans from the amino acid methionine. While the initial step is SO_4^{2-} activation to PAPS, S is added to methionine by the sulfate assimilatory reduction of PAPS, a pathway not found in metazoans [40–43]. Therefore, these amino acids are sources of S in animals via ingestion. In other biomolecules, sulfate groups are transferred from PAPS by a sulfonation pathway, which is found in metazoans [41,43]. Therefore, inorganic SO_4^{2-} from some source is required by animals. The renal reabsorption of SO_4^{2-} is likely part of the source, but the source is also supplied by the direct uptake of SO_4^{2-} from the water, which we observed in our experiments.

In freshwater nymphs of Plecoptera, Ephemeroptera, and Trichoptera, Scheibener et al. [28] measured the uptake of SO_4^{2-} and found that this uptake was inhibited by increased Na^+ water concentrations, suggesting the presence of a $\text{Na}^+/\text{SO}_4^{2-}$ -cotransporter. Buchwalter et al. [29] identified similar SO_4^{2-} transporters in the mayfly, *Neocloeon tranguifer*, but the localization of these transporters was not determined. This research also observed that SO_4^{2-} uptake increased with an increasing SO_4^{2-} water concentration.

In conclusion, our study, along with studies from the Buchwalter laboratory [28,29], suggests that there is direct uptake of SO_4^{2-} from the water in these four groups of freshwater animals. Additionally, there is some evidence that this uptake may increase with the water concentration of SO_4^{2-} . However, the uptake of SO_4^{2-} from the water is not the only source of S, and S from food likely contributes to the SO_4^{2-} excreted by these animals. Therefore, elevated water SO_4^{2-} may interact with other ions to have ionoregulatory effects in freshwater animals that could cause the effects observed by more traditional ecotoxicological studies.

A next step for research on any of these freshwater animals would be to sequence, locate, and functionally characterize any SO_4^{2-} -transporters on their gills or other external epithelial membranes, as has been done for other ions [80–83]. Such information would clarify the potential interactions between SO_4^{2-} and other ions, such as Na^+ , when these ions are elevated in freshwaters. This will more completely identify the potential pathways for adverse outcomes [84] for elevated SO_4^{2-} in freshwaters and better support risk assessments, leading to the development of water-quality benchmarks or criteria.

Supplementary Materials: The following are available online at www.mdpi.com/2073-4441/12/5/1496/s1, Table S1: Summary statistics (mean, standard error (SE), and n for all variables used in the equations to estimate J_{in} , J_{out} , and J_{net} ($\mu\text{M g}^{-1} \text{day}^{-1}$).

Author Contributions: Conceptualization, M.B.G. and J.M.L.; methodology, M.B.G., J.M.L. and H.H.; validation, M.B.G. and H.H.; formal analysis, M.B.G.; investigation, M.B.G., J.M.L. and H.H.; resources, M.B.G. and J.M.L.; data curation, M.B.G. and H.H.; writing—original draft preparation, M.B.G. and H.H.; writing—review and editing, M.B.G. and J.M.L.; visualization, M.B.G. and supervision, M.B.G. and J.M.L.; All authors have read and agreed to the published version of the manuscript.

Funding: This study is based on work supported by the USEPA.

Acknowledgments: M. A. McGregor and staff of the Kentucky Department of Fish and Wildlife Resources' Center for Mollusk Conservation (Frankfort, KY) cultured and supplied us with the paper floater adults. W. Thoeny (Pegasus Technical Services, Cincinnati, OH) assisted in the laboratory. The modification of the calculations for use with sulfur stable isotope data were reviewed by C. Wood (University of British Columbia, Vancouver, BC, Canada). Earlier drafts of this manuscript were reviewed and improved by comments from K. Fritz, S. Cormier (U.S. Environmental Protection Agency, Office of Research and Development, Cincinnati, OH) and three anonymous peer reviewers. This manuscript was prepared by USEPA, ORD, National Center for Environmental Assessment, Cincinnati Division and National Exposure Research Laboratory, Systems Exposure Division. It has been subjected to the agency's peer and administration review and approved for publication. However, the views expressed are those of the authors and do not necessarily represent the views or policies of the USEPA. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the USEPA.

Conflicts of interest: The authors declare no conflicts of interest.

Availability of data: The compiled data set used in these analyses can be viewed or downloaded from USEPA's Science Hub at <https://doi.org/10.23719/1504445>.

References

- Griffith, M.; Zheng, L.; Cormier, S.M. Using extirpation to evaluate ionic tolerance of freshwater fish. *Environ. Toxicol. Chem.* **2017**, *37*, 871–883, doi:10.1002/etc.4022.
- Cormier, S.M.; Suter, G.; Zheng, L. Derivation of a benchmark for freshwater ionic strength. *Environ. Toxicol. Chem.* **2012**, *32*, 263–271, doi:10.1002/etc.2064.
- Elphick, J.R.; Bergh, K.D.; Bailey, H.C. Chronic toxicity of chloride to freshwater species: Effects of hardness and implications for water quality guidelines. *Environ. Toxicol. Chem.* **2010**, *30*, 239–246, doi:10.1002/etc.365.
- Lasier, P.J.; Hardin, I.R. Observed and predicted reproduction of *Ceriodaphnia dubia* exposed to chloride, sulfate, and bicarbonate. *Environ. Toxicol. Chem.* **2010**, *29*, 347–358, doi:10.1002/etc.29.
- Farag, A.M.; Harper, D.D. The chronic toxicity of sodium bicarbonate, a major component of coal bed natural gas produced waters. *Environ. Toxicol. Chem.* **2014**, *33*, 532–540, doi:10.1002/etc.2455.
- Soucek, D.J.; Linton, T.K.; Tarr, C.D.; Dickinson, A.; Wickramanayake, N.; Delos, C.G.; Cruz, L.A. Influence of water hardness and sulfate on the acute toxicity of chloride to sensitive freshwater invertebrates. *Environ. Toxicol. Chem.* **2011**, *30*, 930–938, doi:10.1002/etc.454.
- Griffith, M.; Norton, S.B.; Alexander, L.C.; Pollard, A.I.; LeDuc, S.D. The effects of mountaintop mines and valley fills on the physicochemical quality of stream ecosystems in the central Appalachians: A review. *Sci. Total Environ.* **2012**, *417*, 1–12, doi:10.1016/j.scitotenv.2011.12.042.
- Cowie, R.; Williams, M.W.; Wireman, M.; Runkel, R.L. Use of Natural and Applied Tracers to Guide Targeted Remediation Efforts in an Acid Mine Drainage System, Colorado Rockies, USA. *Water* **2014**, *6*, 745–777, doi:10.3390/w6040745.
- Nordstrom, D.K. Hydrogeochemical processes governing the origin, transport and fate of major and trace elements from mine wastes and mineralized rock to surface waters. *Appl. Geochem.* **2011**, *26*, 1777–1791, doi:10.1016/j.apgeochem.2011.06.002.
- Iii, C.A.C.; Brightbill, R.A.; Langland, M.J. Abandoned Mine Drainage in the Swatara Creek Basin, Southern Anthracite Coalfield, Pennsylvania, USA: 1. Stream Water Quality Trends Coinciding with the Return of Fish. *Mine Water Environ.* **2010**, *29*, 176–199, doi:10.1007/s10230-010-0112-6.
- Elphick, J.R.; Davies, M.; Gilron, G.; Canaria, E.C.; Lo, B.; Bailey, H.C. An aquatic toxicological evaluation of sulfate: The case for considering hardness as a modifying factor in setting water quality guidelines. *Environ. Toxicol. Chem.* **2010**, *30*, 247–253, doi:10.1002/etc.363.
- Davies, T.D.; Hall, K.J. Importance of calcium in modifying the acute toxicity of sodium sulphate to *Hyalella azteca* and *Daphnia magna*. *Environ. Toxicol. Chem.* **2007**, *26*, 1243–1247, doi:10.1897/06-510r.1.
- Soucek, D.J. Comparison of hardness- and chloride-regulated acute effects of sodium sulfate on two freshwater crustaceans. *Environ. Toxicol. Chem.* **2007**, *26*, 773–779, doi:10.1897/06-229r.1.
- Soucek, D.J.; Dickinson, A. Full-life chronic toxicity of sodium salts to the mayfly *Neocloeon triangulifer* in tests with laboratory cultured food. *Environ. Toxicol. Chem.* **2015**, *34*, 2126–2137, doi:10.1002/etc.3038.
- Horisberger, J.-D. Recent Insights into the Structure and Mechanism of the Sodium Pump. *Physiology* **2004**, *19*, 377–387, doi:10.1152/physiol.00013.2004.
- Ivanis, G.; Esbaugh, A.J.; Perry, S.F. Branchial expression and localization of SLC9A2 and SLC9A3 sodium/hydrogen exchangers and their possible role in acid-base regulation in freshwater rainbow trout (*Oncorhynchus mykiss*). *J. Exp. Biol.* **2008**, *211*, 2467–2477, doi:10.1242/jeb.017491.
- Pullikuth, A.; Aimanova, K.; Kang'ethe, W.; Sanders, H.R.; Gill, S.S. Molecular characterization of sodium/proton exchanger 3 (NHE3) from the yellow fever vector, *Aedes aegypti*. *J. Exp. Biol.* **2006**, *209*, 3529–3544, doi:10.1242/jeb.02419.
- Soucek, D.J.; Mount, D.R.; Dickinson, A.; Hockett, J.R. Influence of dilution water ionic composition on acute major ion toxicity to the mayfly *Neocloeon triangulifer*. *Environ. Toxicol. Chem.* **2018**, *37*, 1330–1339, doi:10.1002/etc.4072.
- Erickson, R.J.; Mount, D.R.; Highland, T.L.; Hockett, J.R.; Hoff, D.J.; Jenson, C.T.; Norberg-King, T.J.; Peterson, K.N. The acute toxicity of major ion salts to *Ceriodaphnia dubia*. II. Empirical relationships in binary salt mixtures. *Environ. Toxicol. Chem.* **2016**, *36*, 1525–1537, doi:10.1002/etc.3669.

20. Mount, D.R.; Erickson, R.J.; Highland, T.L.; Hockett, J.R.; Hoff, D.J.; Jenson, C.T.; Norberg-King, T.J.; Peterson, K.N.; Polaske, Z.M.; Wisniewski, S.; et al. The acute toxicity of major ion salts to *Ceriodaphnia dubia*: I. influence of background water chemistry. *Environ. Toxicol. Chem.* **2016**, *35*, 3039–3057, doi:10.1002/etc.3487.
21. Griffith, M. Toxicological perspective on the osmoregulation and ionoregulation physiology of major ions by freshwater animals: Teleost fish, crustacea, aquatic insects, and Mollusca. *Environ. Toxicol. Chem.* **2016**, *36*, 576–600, doi:10.1002/etc.3676.
22. Romeu, F.G.; Maetz, J. The Mechanism of Sodium and Chloride Uptake by the Gills of a Fresh-Water Fish, *Carassius auratus*. *J. Gen. Physiol.* **1964**, *47*, 1195–1207, doi:10.1085/jgp.47.6.1195.
23. de Renzis, G.; Maetz, J. Studies on the mechanism of chloride absorption by the goldfish gill: Relation with acid-base regulation. *J. Exp. Biol.* **1973**, *59*, 339–358.
24. Shaw, J. The absorption of sodium ions by the crayfish, *Astacus pallipes* Lereboullet: II. The effect of the external anion. *J. Exp. Biol.* **1960**, *37*, 534–547.
25. McMahon, B.; Stuart, S. The physiological problems of crayfish in acid waters. In *Acid Toxicity and Aquatic Animals*; Cambridge University Press (CUP): Cambridge, UK, 1989; Volume 34, pp. 171–200.
26. Dietz, T.H.; Udoetok, A.S.; Cherry, J.S.; Byrne, H.S.A. Kidney function and sulfate uptake and loss in the freshwater bivalve *Toxolasma texasensis*. *Boil. Bull.* **2000**, *199*, 14–20, doi:10.2307/1542702.
27. Larsen, E.H.; Simonsen, K. Sulfate transport in toad skin: Evidence for mitochondria-rich cell pathways in common with halide ions. *Comp. Biochem. Physiol. Part A Physiol.* **1988**, *90*, 709–714, doi:10.1016/0300-9629(88)90688-3.
28. Scheibener, S.; Conley, J.M.; Buchwalter, D.B. Sulfate transport kinetics and toxicity are modulated by sodium in aquatic insects. *Aquat. Toxicol.* **2017**, *190*, 62–69, doi:10.1016/j.aquatox.2017.06.027.
29. Buchwalter, D.B.; Scheibener, S.; Chou, H.; Soucek, D.; Elphick, J. Are sulfate effects in the mayfly *Neocloeon triangulifer* driven by the cost of ion regulation? *Philos. Trans. R. Soc. B Biol. Sci.* **2018**, *374*, 20180013, doi:10.1098/rstb.2018.0013.
30. Dietz, T.H.; Byrne, R.A. Measurement of sulfate uptake and loss in the freshwater bivalve *Dreissena polymorpha* using a semi-microassay. *Can. J. Zool.* **1999**, *77*, 331–336, doi:10.1139/z98-215.
31. Potts, W.T.W. The inorganic composition of the blood of *Mytilus edulis* and *Anodonta cygnea*. *J. Exp. Biol.* **1954**, *31*, 376–385.
32. Malley, D.F.; Huebner, J.D.; Donkersloot, K. Effects on ionic composition of blood and tissues of *Anodonta grandis grandis* (Bivalvia) of an addition of aluminum and acid to a lake. *Arch. Environ. Contam. Toxicol.* **1988**, *17*, 479–491, doi:10.1007/bf01055513.
33. Andrews, P. Über den Blutchemismus des Flukrebses *Orconectes limosus* und seine Veränderung im Laufe des Jahres. *J. Comp. Physiol. A* **1967**, *57*, 7–43, doi:10.1007/bf00298221.
34. Wood, C.M.; McMahon, B. Mechanisms of acid-base and ionoregulation in white suckers (*Catostomus commersoni*) in natural soft water. *J. Comp. Physiol. B* **1984**, *154*, 35–46, doi:10.1007/bf00683214.
35. Nakada, T.; Zandi-Nejad, K.; Kurita, Y.; Kudo, H.; Broumand, V.; Kwon, C.Y.; Mercado, A.; Mount, D.B.; Hirose, S. Roles of Slc13a1 and Slc26a1 sulfate transporters of eel kidney in sulfate homeostasis and osmoregulation in freshwater. *Am. J. Physiol. Integr. Comp. Physiol.* **2005**, *289*, R575–R585, doi:10.1152/ajpregu.00725.2004.
36. Linker, P.H. Glycosaminoglycans in *Anodonta californiensis*, a Freshwater Mussel. *Boil. Bull.* **1993**, *185*, 263–276, doi:10.2307/1542006.
37. Luquet, G.; Fernández, M.S.; Badou, A.; Guichard, N.; Le Roy, N.; Corneillat, M.; Alcaraz, G.; Arias, J.L. Comparative Ultrastructure and Carbohydrate Composition of Gastroliths from Astacidae, Cambaridae and Parastacidae Freshwater Crayfish (Crustacea, Decapoda). *Biomolecules* **2012**, *3*, 18–38, doi:10.3390/biom3010018.
38. Yamada, S.; Sugahara, K.; Özbek, S. Evolution of glycosaminoglycans. *Commun. Integr. Boil.* **2011**, *4*, 150–158, doi:10.4161/cib.4.2.14547.
39. Cássaro, C.M.; Dietrich, C.P. Distribution of sulfated mucopolysaccharides in invertebrates. *J. Boil. Chem.* **1977**, *252*, 2254–2261.
40. Hudson, B.H.; York, J.D. Roles for nucleotide phosphatases in sulfate assimilation and skeletal disease. *Adv. Boil. Regul.* **2012**, *52*, 229–238, doi:10.1016/j.advenzreg.2011.11.002.
41. Klaassen, C.D.; Boles, J.W. The importance of 3'-phosphoadenosine 5'-phosphosulfate (PAPS) in the regulation of sulfation. *FASEB J.* **1997**, *11*, 404–418, doi:10.1096/fasebj.11.6.9194521.

42. Sun, M.; Leyh, T.S. Channeling in Sulfate Activating Complexes†. *Biochemistry* **2006**, *45*, 11304–11311, doi:10.1021/bi060421e.
43. Boom, J.V.D.; Heider, D.; Martin, S.R.; Pastore, A.; Mueller, J.W. 3'-Phosphoadenosine 5'-phosphosulfate (PAPS) synthases, naturally fragile enzymes specifically stabilized by nucleotide binding. *J. Boil. Chem.* **2012**, *287*, 17645–17655, doi:10.1074/jbc.M111.325498.
44. Bradley, T.J. Hyper-regulators: Life in fresh water Hyper-regulators: Life in fresh water. In *Animal Osmoregulation*; Oxford University Press (OUP): Oxford, UK, 2008; pp. 86–110.
45. USEPA. *Methods for Measuring the Acute Toxicity of Effluents and Receiving Waters to Freshwater and Marine Organisms*; U.S. Environmental Protection Agency, Ed.; U.S. Environmental Protection Agency, Office of Water: Washington, DC, USA, 2002.
46. Gordon, D.A.; Smith, M.E.; Wratschko, M.; Agard, D.; Holden, L.; Wilcox, S.; Lazorchak, J. A new approach for the laboratory culture of the fathead minnow, *Pimephales promelas*. *Environ. Toxicol. Chem.* **2013**, *33*, 126–133, doi:10.1002/etc.2396.
47. Smith, M.E.; Lazorchak, J.; Herrin, L.E.; Brewer-Swartz, S.; Thoeny, W.T. A reformulated, reconstituted water for testing the freshwater amphipod, *Hyalella azteca*. *Environ. Toxicol. Chem.* **1997**, *16*, 1229–1233, doi:10.1002/etc.5620160618.
48. Wang, N.; Consbrock, R.A.; Ingersoll, C.G.; Hardesty, D.K.; Brumbaugh, W.G.; Hammer, E.; Bauer, C.R.; Mount, D.R. Acute and chronic toxicity of sodium sulfate to four freshwater organisms in water-only exposures. *Environ. Toxicol. Chem.* **2015**, *35*, 115–127, doi:10.1002/etc.3148.
49. Romano, N.; Zeng, C. Effects of potassium on nitrate mediated alterations of osmoregulation in marine crabs. *Aquat. Toxicol.* **2007**, *85*, 202–208, doi:10.1016/j.aquatox.2007.09.004.
50. Dietz, T.H.; Wilcox, S.J.; Silverman, H.; Byrne, R.A. Effects of hyperosmotic challenge on the freshwater bivalve *Dreissena polymorpha*: Importance of K⁺. *Can. J. Zool.* **1997**, *75*, 697–705, doi:10.1139/z97-090.
51. Henry, M.; Chester, D.; Mauck, W. Role of artificial burrows in Hexagenia toxicity tests: Recommendations for protocol development. *Environ. Toxicol. Chem.* **1986**, *5*, 553–559, doi:10.1002/etc.5620050607.
52. Revesz, K.; Coplen, T.B. Determination of the $\delta^{34}\text{S}$ of Total Sulfur in Solids: RSIL Lab Code 1800. In *Techniques and Methods*; US Geological Survey: Reston, VA, USA, 2006; pp. 1–31.
53. USEPA. *Methods for the Determination of Inorganic Substances in Environmental Samples*; U.S. Environmental Protection Agency, Office of Research and Development: Cincinnati, OH, USA, 1993.
54. Revesz, K.; Qi, H.; Coplen, T.B. Determination of the $\delta^{34}\text{S}$ of sulfate in water; RSIL lab code 1951. In *Techniques and Methods*; US Geological Survey: Reston, VA, USA, 2006; pp. 1–31.
55. Coplen, T.B. Guidelines and recommended terms for expression of stable-isotope-ratio and gas-ratio measurement results. *Rapid Commun. Mass Spectrom.* **2011**, *25*, 2538–2560, doi:10.1002/rcm.5129.
56. Cobelli, C.; Toffolo, G.; Bier, D.M.; Nosadini, R. Models to interpret kinetic data in stable isotope tracer studies. *Am. J. Physiol. Metab.* **1987**, *253*, E551–E564, doi:10.1152/ajpendo.1987.253.5.e551.
57. Cobelli, C.; Toffolo, G.; Foster, D.M. Tracer-to-tracee ratio for analysis of stable isotope tracer data: Link with radioactive kinetic formalism. *Am. J. Physiol. Metab.* **1992**, *262*, E968–E975, doi:10.1152/ajpendo.1992.262.6.e968.
58. Wood, C.M. Acid-base and ionic exchanges at gills and kidney after exhaustive exercise in the rainbow trout. *J. Exp. Biol.* **1988**, *136*, 461–481.
59. Wood, C.M.; Wheatly, M.G.; Höbe, H. The mechanisms of acid-base and ionoregulation in the freshwater rainbow trout during environmental hyperoxia and subsequent normoxia. III. Branchial exchanges. *Respir. Physiol.* **1984**, *55*, 175–192, doi:10.1016/0034-5687(84)90021-5.
60. Gonzalez, R.J.; Dunson, W.A. Adaptations of sodium balance to low pH in a sunfish (*Enneacanthus obesus*) from naturally acidic waters. *J. Comp. Physiol. B* **1987**, *157*, 555–566, doi:10.1007/bf00700975.
61. Robinson, R.B. Reference and intercomparison materials for stable isotopes of light elements. In *Proceedings of a Consultants Meeting Vienna, Austria, 1–3 December 1993*; International Atomic Energy Agency: Vienna, Austria, 1995; pp. 39–45.
62. Stobbs, R.H. The effect of some anions and cations upon the fluxes and net uptake of chloride in the larva of *Aedes aegypti* (L.), and the nature of the uptake mechanisms for sodium and chloride. *J. Exp. Biol.* **1967**, *47*, 35–57.
63. Chen, Y.-Y.; Lu, F.-I.; Hwang, P.-P. Comparisons of calcium regulation in fish larvae. *J. Exp. Zool.* **2003**, *295*, 127–135, doi:10.1002/jez.a.10195.

64. Wilcox; Dietz Potassium transport in the freshwater bivalve *Dreissena polymorpha*. *J. Exp. Biol.* **1995**, *198*, 861–868.
65. Frain, W.J. The effect of external sodium and calcium concentrations on sodium fluxes by salt-depleted and non-depleted minnows, *Phoxinus phoxinus* (L.). *J. Exp. Biol.* **1987**, *131*, 417–425.
66. Chasiotis, H.; Kolosov, D.; Kelly, S. Permeability properties of the teleost gill epithelium under ion-poor conditions. *Am. J. Physiol. Integr. Comp. Physiol.* **2012**, *302*, R727–R739, doi:10.1152/ajpregu.00577.2011.
67. Dietz, T.H.; Byrne, R.A.; Lynn, J.W.; Silverman, H. Paracellular solute uptake by the freshwater zebra mussel *Dreissena polymorpha*. *Am. J. Physiol. Integr. Comp. Physiol.* **1995**, *269*, R300–R307, doi:10.1152/ajpregu.1995.269.2.r300.
68. McDonald, D.G.; Rogano, M.S. Ion Regulation by the Rainbow Trout, *Salmo gairdneri*, in Ion-Poor Water. *Physiol. Zool* **1986**, *59*, 318–331, doi:10.1086/physzool.59.3.30156103.
69. Wood, C.M.; Gilmour, K.M.; Pärt, P. Passive and active transport properties of a gill model, the cultured branchial epithelium of the freshwater rainbow trout (*Oncorhynchus mykiss*). *Comp. Biochem. Physiol. Part. A Mol. Integr. Physiol.* **1998**, *119*, 87–96, doi:10.1016/s1095-6433(97)00403-0.
70. Takahashi, H.; Kopriva, S.; Giordano, M.; Saito, K.; Hell, R. Sulfur Assimilation in Photosynthetic Organisms: Molecular Functions and Regulations of Transporters and Assimilatory Enzymes. *Annu. Rev. Plant. Biol.* **2011**, *62*, 157–184, doi:10.1146/annurev-arplant-042110-103921.
71. McArthur, J.V.; Moorhead, K.K. Characterization of riparian species and stream detritus using multiple stable isotopes. *Oecologia* **1996**, *107*, 232–238, doi:10.1007/bf00327907.
72. Markovich, D.; Romano, A.; Storelli, C.; Verri, T. Functional and structural characterization of the zebrafish Na⁺-sulfate cotransporter 1 (NaS1) cDNA and gene (slc13a1). *Physiol. Genom.* **2008**, *34*, 256–264, doi:10.1152/physiolgenomics.90234.2008.
73. Katoh, F.; Tresguerres, M.; Lee, K.M.; Kaneko, T.; Aida, K.; Goss, G.G. Cloning of rainbow trout SLC26A1: Involvement in renal sulfate secretion. *Am. J. Physiol. Integr. Comp. Physiol.* **2006**, *290*, R1468–R1478, doi:10.1152/ajpregu.00482.2005.
74. Maddrell, S.H.P.; Phillips, J.E. Active transport of sulphate ions by the Malpighian tubules of larvae of the mosquito *Aedes campestris*. *J. Exp. Biol.* **1975**, *62*, 367–378.
75. Maddrell, S.H.P.; Phillips, J.E. Induction of sulphate transport and hormonal control of fluid secretion by Malpighian Tubules of larvae of the mosquito *Aedes taeniorhynchus*. *J. Exp. Biol.* **1978**, *72*, 181–202.
76. Gerencser, G.A.; Cattey, M.A.; Ahearn, G.A. Sulfate/oxalate exchange by lobster hepatopancreatic basolateral membrane vesicles. *Am. J. Physiol. Integr. Comp. Physiol.* **1995**, *269*, R572–R577, doi:10.1152/ajpregu.1995.269.3.r572.
77. Gerencser, G.A.; Ahearn, G.A.; Cattey, M.A. Antiport-driven sulfate secretion in an invertebrate epithelium. *J. Exp. Zool* **1996**, *275*, 269–276, doi:10.1002/(sici)1097-010x(19960701)275:43.0.co;2-n.
78. Cattey, M.A.; Gerencser, G.A.; Ahearn, G.A. Electrogenic H⁺-regulated sulfate-chloride exchange in lobster hepatopancreatic brush-border membrane vesicles. *Am. J. Physiol. Integr. Comp. Physiol.* **1992**, *262*, R255–R262, doi:10.1152/ajpregu.1992.262.2.r255.
79. Cattey, M.A.; Gerencser, G.A.; Ahearn, G.A. Electrogenic Coupling of Sulfate Secretion to Chloride Transport in Lobster Hepatopancreas. In *Blood and Tissue Oxygen Carriers*; Springer Science and Business Media LLC: Berlin, Germany, 1994; Volume 19, pp. 109–120.
80. Horng, J.-L.; Hwang, P.-P.; Shih, T.-H.; Wen, Z.-H.; Lin, C.-S.; Lin, L.-Y. Chloride transport in mitochondrion-rich cells of euryhaline tilapia (*Oreochromis mossambicus*) larvae. *Am. J. Physiol. Physiol.* **2009**, *297*, C845–C854, doi:10.1152/ajpcell.00218.2009.
81. Choe, K.P.; O'Brien, S.; Evans, D.H.; Toop, T.; Edwards, S. Immunolocalization of Na⁺/K⁺-ATPase, carbonic anhydrase II, and vacuolar H⁺-ATPase in the gills of freshwater adult lampreys, *Geotria australis*. *J. Exp. Zool* **2004**, *301*, 654–665, doi:10.1002/jez.a.60.
82. Filippov, V.; Aimanova, K.; Gill, S.S. Expression of an *Aedes aegypti* cation-chloride cotransporter and its *Drosophila* homologues. *Insect Mol. Biol.* **2003**, *12*, 319–331, doi:10.1046/j.1365-2583.2003.00415.x.

83. Gao, Y.; Wheatly, M.G. Characterization and expression of plasma membrane Ca^{2+} ATPase (PMCA3) in the crayfish *Procambarus clarkii* antennal gland during molting. *J. Exp. Boil.* **2004**, *207*, 2991–3002, doi:10.1242/jeb.01101.
84. Ankley, G.T.; Bennett, R.; Erickson, R.J.; Hoff, D.J.; Hornung, M.W.; Johnson, R.D.; Mount, D.R.; Nichols, J.W.; Russom, C.L.; Schmieder, P.K.; et al. Adverse outcome pathways: A conceptual framework to support ecotoxicology research and risk assessment. *Environ. Toxicol. Chem.* **2010**, *29*, 730–741, doi:10.1002/etc.34.



© 2020 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<http://creativecommons.org/licenses/by/4.0/>).