Published July, 2010

Impact of Drought on Wastewater Contaminants in an Urban Water Supply

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The concentrations of selected wastewater contaminants, including conductivity, nitrate, and pharmaceuticals and endocrine disrupting compounds (EDCs), were monitored from 2003 to 2007 in Lake Mead, the raw (untreated) drinking water for southern Nevada. Monitoring was also conducted in two inflows to Lake Mead: the Colorado River and the wastewater-dominated Las Vegas Wash. There was a statistically significant increase in source water conductivity, nitrate, and pharmaceutical and EDC concentrations over this time period, concomitant with a statistically significant decline in the volume of Lake Mead. There was no statistically significant increase in conductivity and nitrate in the Colorado River or the Las Vegas Wash over this period, nor was there an increase in flow of the Las Vegas Wash or Colorado River. Thus, the deterioration of source drinking water quality is due to the decrease in the volume of Lake Mead which has been attributed to drought. This phenomenon may also be a harbinger of how water quality may be adversely affected by climate change as patterns of surface water flow shift and treated wastewater becomes a larger fraction of surface water flow in some areas.

Among the many potential effects of drought, altered precipitation patterns are of primary concern to drinking water utilities in their direct impact on the ability to ensure both sufficient supply and quality of drinking water. It is already evident that burgeoning human population has put a strain on freshwater resources and has adversely affected water quality throughout the world (UNESCO, 2006). Even in the United States, where government regulations and treatment technology have drastically reduced the occurrence of disease associated with unclean drinking water, anthropogenic compounds continue to be detected in drinking waters (Benotti et al., 2009; USEPA, 2005). In arid areas like the American Southwest, drought can affect surface water flow and alter water budgets. Additionally, there is a growing concern that the drought which has gripped the American Southwest in recent years is more indicative of long-term changes in hydrologic processes attributed to climate change (Barnett et al., 2004, 2008). Apart from the availability of water, the quality of surface water will deteriorate as treated wastewater becomes a larger fraction of surface water flow.

The influence of wastewater on drinking water supplies is an important issue to water suppliers, scientists, and regulators. The deterioration of water quality due to wastewater can manifest itself in many ways, from increased frequencies of detection of microbial indicators, such as fecal coliforms, to elevated concentrations of salts, nutrients, or other contaminants. Pharmaceuticals and EDCs are wastewater contaminants (Glassmeyer et al., 2005; Snyder et al., 2003) which have been detected in both surface waters (Kolpin et al., 2002) and drinking waters (Benotti et al., 2009). Scientists and regulators have linked the presence of pharmaceuticals and EDCs in wastewater-dominated environments to adverse toxicological effects such as endocrine disruption in indigenous species (Routledge et al., 1998; Snyder et al., 2004). However, to date there have been no demonstrated adverse human-health effects posed by trace-level concentrations of these compounds in drinking water (Daughton and Ternes 1999; Snyder et al., 2006). Regardless, the degree to which the mere presence of these compounds in water has drawn interest across disciplines is illustrated by the voices of concern stemming from medical professionals, environmental scientists, drinking water municipalities, government agencies, and the general media (Daughton and Ternes 1999; Donn et al., 2008; Jones et al., 2005; Kuehn 2008; Snyder et al., 2003).

This study documents (i) that concentrations of selected wastewater contaminants, including pharmaceuticals and EDCs have been increasing in the source drinking water for southern Nevada

J. Environ. Qual. 39:1196–1200 (2010)
doi:10.2134/jeq2009.0072
Published online 13 Nov. 2009.
Received 27 Feb. 2009.
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Abbreviations: EDCs, endocrine disrupting compounds.

in recent years, and (ii) this increase is largely due to altered patterns of surface water flow rather than increased loading of these compounds from wastewater. Thus, it serves as an illustration of how source drinking water quality in some areas is adversely affected by processes that affect surface water hydrology, such as drought and climate change.

Study Site

Lake Mead and the Colorado River (Fig. 1) serve the water needs for more than 30 million Americans, including the three cities in the Las Vegas Valley: Las Vegas, North Las Vegas, and Henderson (total population 2.0 million). Most of the drinking water for the Valley is drawn from one location within Lake Mead, and drinking water quality has been monitored throughout the Lake Mead system for several decades. Monthly monitoring of source water for pharmaceuticals and EDCs has occurred since 2003. The presence of contaminants in source drinking water is primarily attributed to the Las Vegas Wash (LaBounty and Burns, 2005), the only surface drainage feature of the Las Vegas Valley and the conduit for treated effluent from the Valley's three wastewater treatment plants back to Lake Mead. Many water quality parameters have been measured in the Wash for over two decades, and pharmaceuticals and EDCs have been measured since 1997 (Snyder et al., 1999). Though the flow of the Wash is small, historically averaging just 1.4% of the total flow into Lake Mead, it is almost entirely (85%) wastewater. There are no other major urban areas discharging wastewater into the Colorado River or Lake Mead.

Materials and Methods

Conductivity and nitrate (NO_3^--N) concentrations were obtained from monitoring programs conducted by the Southern Nevada Water Authority between 1 Jan. 2003 and 31 Dec. 2007. Three sites were targeted to provide an indication of the influence of water qualities from the Las Vegas Wash and the Colorado River on the location of the drinking water intake in Lake Mead (Fig. 1). Monthly concentrations of pharmaceuticals and EDCs were measured in the Las Vegas Wash, as well as the source drinking water between May 2003 and December 2007. Sample collection and analyses were conducted in accordance with two separate methodologies. The first, identified as "Method 1," was used between May 2003 and December 2005 and employed a combination of externally-calibrated LC-MS/MS and GC–MS/MS methods (Trenholm et al., 2006; Vanderford et al., 2003). The second, identified as "Method 2," was used between January 2006 and December 2007 and employed a combination of isotope-dilution LC-MS/MS and GC–MS/MS methods (Snyder et al., 2008; Vanderford and Snyder 2006). Both methods included analysis of blanks and matrix spikes to as part of a rigorous QA/QC process which is discussed in the aforementioned publications. For purposes of discussion, the data obtained from each method are treated as separate datasets and should not be combined due to differences in the analytical approaches (e.g., different detection limits, or the potential for biased results due to the matrix effects associated with externally calibrated methods). Pharmaceutical and EDC raw data are available in the Supplemental Information. All Las Vegas Wash and Colorado River samples were collected from the surface of the Wash or River using a grab sampler. All source drinking waters were collected from a tap fed by the intake structure, which draws water from an elevation of 305 m above sea level. Lake Mead elevation declined from 352 to 340 m above sea level between January 2003 and December 2007, and in spite of this decline, source drinking water was always withdrawn from the same water mass below the epilimnion.

Flow data for the Las Vegas Wash were obtained from the U.S. Geological Survey's National Water Information System for Nevada (http://waterdata.usgs.gov/nv/nwis/uv/, Station #09419800). Flow data for the Colorado River were obtained from the U.S. Geological Survey's National Water Information System for Arizona (http://waterdata.usgs.gov/az/nwis/uv/, Station #09404200). Lake Mead capacity was calculated from the daily lake volumes (obtained from U.S. Bureau of Reclamation: http://www.usbr.gov/lc/region/g4000/archives.html and Janie Jo Smith, written communication), divided by the maximum capacity: 3.2×10^{13} L (25,877,000 acre-ft). The flows of the Las Vegas Wash and the Colorado River, as well as the capacity of Lake Mead are presented in Fig. 2.

Results and Discussion

Two data sets showing the summed concentrations of atrazine; carbamazepine; n,n-dietyl-meta-toluamide (DEET), diazepam; diclofenac; dilantin; estradiol; estrone; ethynylestradiol; fluoxetine; gemfibrozil; meprobamate; naproxen; sulfamethoxazole; testosterone; and trimethoprim measured in the Las Vegas Wash and source drinking water are shown in Fig. 3A. Compounds which were not detected (reported as < X in the Supporting Information, where X equals the method reporting limit) were assigned a value of 0 to create Fig. 3A. It is important to note that diazepam, estradiol, and ethynylestradiol were never detected in source drinking water (see Supplemental Information). The circles and squares represent measurements made from the Method 1 and Method 2 analyses, respectively. As previously mentioned, these datasets are treated as separate, and are not combined due to differences in the analytical methodologies. The concentration of nitrate in the Las Vegas Wash, the Colorado River, and source drinking water are shown in Fig. 3B. Values for conductivity in the Las Vegas Wash, Colorado River, and source drinking water are shown in Fig. 3C.

A statistical analysis of both pharmaceutical and EDC dataset for significance of slope indicate that summed source water concentration increased at a rate significantly different from zero slope with > 99% confidence (Fig. 3A). The rate of concentration increase was 0.02 ng L^{-1} d^{-1} ($p < 0.0001$) for Method 1 and 0.008 ng L^{-1} d^{-1} ($p = 0.004$) for Method 2. The rate at which pharmaceutical and EDC concentrations increased or decreased in the Las Vegas Wash was not statistically different from zero for Method 1 data. Summed concentrations of pharmaceuticals and EDCs measured by Method 2 decreased at a rate of 1.0 ng L^{-1} d^{-1} ($p < 0.0001$), though this rate is heavily influenced by anomalously low November 2007 data point. Regardless, neither dataset shows an increase in concentrations of these compounds in the Las Vegas Wash. Though the flow of the Las Vegas Wash did increase at a rate that was statistically different from zero (slope = 0.0000006 mL s^{-1} d^{-1} , $p < 0.0001$; Fig. 2), the amount

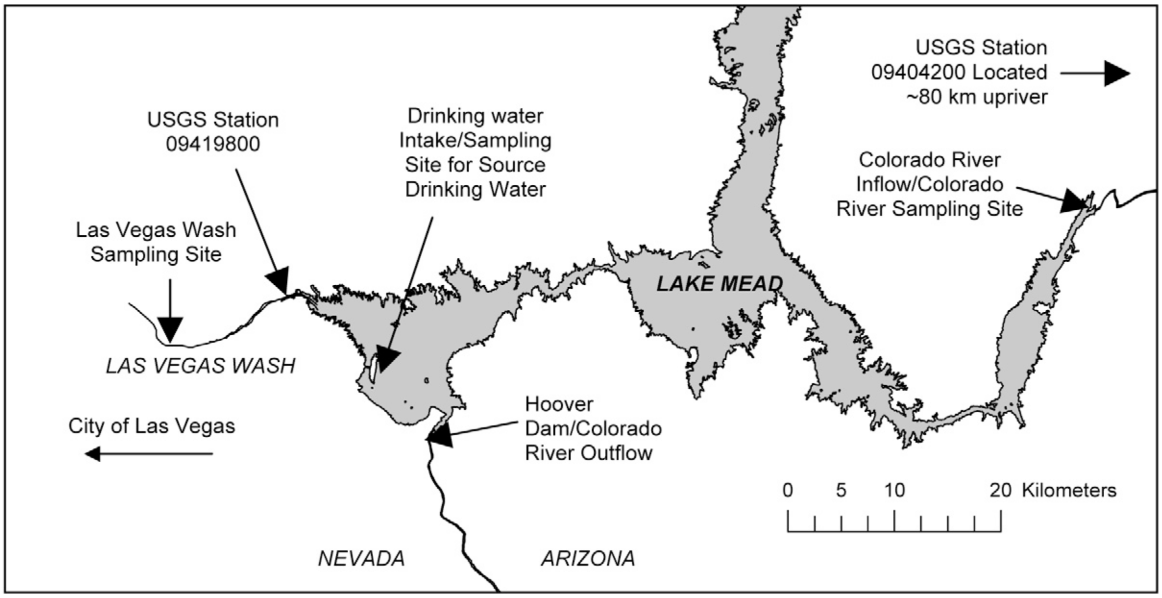

Fig. 1. Map of Lake Mead showing the Las Vegas Wash, the primary source of wastewater-derived pharmaceuticals and endocrine disrupting compounds (EDCs). The monitoring locations for the Las Vegas Wash, and the location of the drinking water intake is noted.

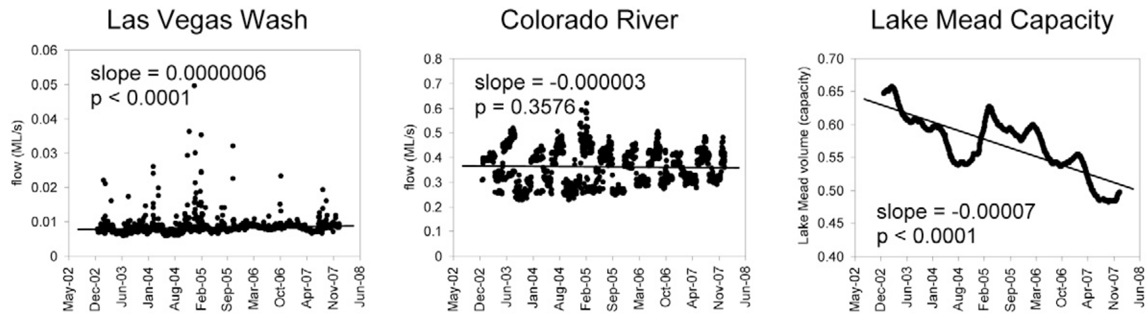

Fig. 2. Flow data for the Las Vegas Wash and the Colorado River, as well as the capacity of Lake Mead between 1 Jan. 2003 and 31 Dec. 2007.

of increase was < 10% over this time period. Thus, the combination of Las Vegas Wash flow and pharmaceutical and concentrations yields a mass loading which increased by 10% far below the doubling (100% increase) of concentration observed in source drinking water over the same period of time. There are no data for the presence of these compounds in the Colorado River site, though concentrations should be negligible as there are no large inputs of wastewater upriver from Lake Mead.

Similar trends are observed for both nitrate and conductivity. Nitrate concentrations in the Las Vegas Wash did not change at a rate statistically different from zero (p = 0.4) between January 1, 2003 and December 31, 2007. Nitrate concentrations decreased in the Colorado River at a rate of 0.00007 mg L^{-1} d^{-1} (p < 0.0001), yet increased in source drinking water at a rate of 0.0002 mg L^{-1} d^{-1} (p < 0.0001) over this same time period. Conductivity in the Las Vegas Wash did not change at a rate statistically different from zero (p = 0.03) between 1 Jan. 2003 and 31 Dec. 2007. Yet, conductivity decreased in the Colorado River at a rate of 0.04 µS cm^{-1} d^{-1} (p < 0.0001) and increased in source drinking water at a rate of 0.05 µS cm^{-1} d^{-1} (p < 0.0001) over this same time period. As was the case with concentrations of pharmaceuticals and EDCs, the increased loading associated with the slight increase in flow of the Las Vegas Wash over this time period does not alone account for the concomitant increase in nitrate and conductivity in source drinking water. This is especially true when one considers that historically, source drinking water is largely composed (95% of water from the Colorado River (LaBounty and Burns, 2005), where concentrations of nitrate and conductivity actually decreased over this time period. Thus, the discrepancy between loading and source water concentration is not explained by a hydrological explanation of a system at steady state. The increase in pharmaceutical and EDC concentrations, nitrate concentrations, and conductivity in source drinking water is due to the decline in volume of Lake Mead between 1 Jan. 2003 and 31 Dec. 2007. During this time, the volume of Lake Mead declined from approximately 65% capacity, to almost 50% capacity (Fig. 2) at a rate of 0.00007 d^{-1} (p < 0.0001).

There are two major influences on the volume of water in Lake Mead: Colorado River flow, and reservoir management. Lake Powell, another large reservoir upriver from Lake Mead is also primarily fed by the Colorado River. Thus, the total volume of water in both reservoirs is dependant on the flow of the Colorado River, but the release from Lake Powell via the Glen Canyon Dam determines the actual inflow to Lake Mead. The Colorado River inflow to Lake Powell was generally below average over the time period discussed in this manuscript, a phenomenon that the U.S. Bureau of Reclamation attributed to drought. In this 5-yr span, only 2005 had an above-average annual inflow to Lake Powell (105%) . Inflow in the other 4 yr

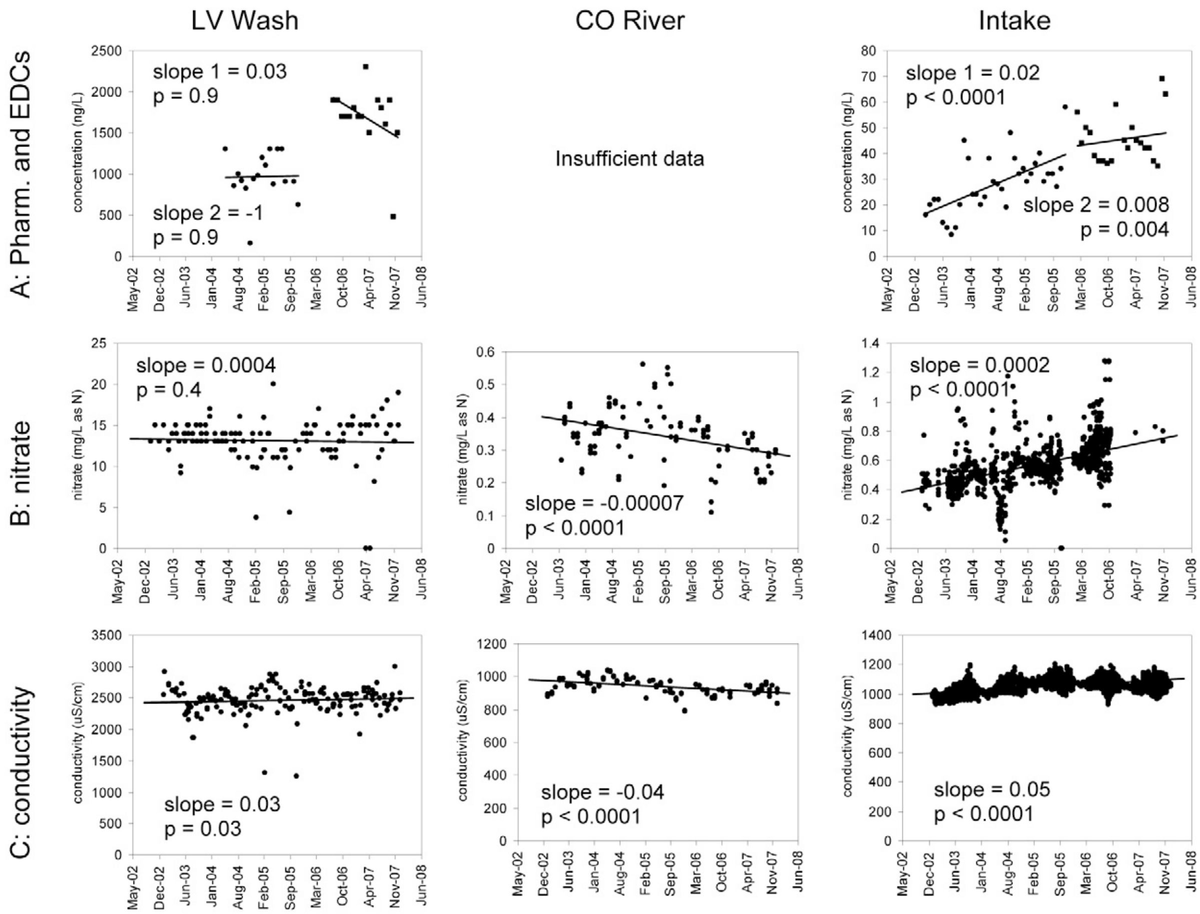

Fig. 3. (A) Summed concentrations of 17 pharmaceuticals and endocrine disrupting compounds (EDCs), (B) nitrate, and (C) conductivity in the Las Vegas Wash, the Colorado River, and in drinking water source water between 1 Jan. 2003 and 31 Dec. 2007.

ranged between 49 and 73% (USBOR, 2009). It is the managed release from Lake Powell which serves as the inflow to Lake Mead, thus inflows to Lake Mead are influenced by both drought and reservoir management practices. While it is true that the volume of water in Lake Mead could be affected if regulators choose to release additional water from Lake Powell, significant changes in reservoir management are not possible given the Colorado River Compact– the agreement by which Colorado River is distributed to U.S. states and Mexico.

The decline in Colorado River flow and Lake Mead volume between 2003 and 2007 may be part of a larger trend in decreasing river flow, which has been linked to climate change. During the 20th century, the average flow of the Colorado River dropped by a factor of two, from approximately 1.9×10^{13} L (15 million acre-ft) in 1900, to approximately 8.6×10^{12} L (7 million acre-ft) in 2000 (USGS 2004). Barnett et al. (2008) concluded that 60% of the observable climate-related trends (including snow-pack on the western Rocky Mountains which serves as the source of the Colorado River) between 1950 and 1999 were attributed to human-induced climate change. Moreover, researchers predict that this trend will continue in the coming decades further straining water resources in the American Southwest (Barnett et al., 2004; Barnett and Pierce 2008; McCabe and Wolock 2007). The link between insufficient water supplies and slowing patterns of surface water flow partially attributed to climate change has been observed in the U.S. Great Plains (Brikowski, 2008). This manuscript furthers this relationship by illustrating how water quality can also be adversely affected by this phenomenon.

Conclusions

As the volume of Lake Mead declines, partly as a result of drought, wastewater will have more of an impact on the source drinking water for Las Vegas and cities down-river likely resulting in higher concentrations of wastewater-derived contaminants. While treatment technologies exist to remove most classes of these contaminants, treatment would be most effective if it were implemented on the wastewater end, as it would mitigate some of the adverse effects that are observed in the environment (e.g., endocrine disruption). However, implementation of additional treatment technologies will carry some energy cost. The irony here is that anthropogenically-driven climate change associated with use of fossil fuels may lead to drought, which may lead to altered patterns of surface water flow, which may lead to increased concentrations of wastewater-derived contaminants in a water supply, which may necessitate the need for additional wastewater treatment requiring additional energy costs burning greater amounts of fossil fuels.

While the most significant threat to people relying on the Colorado River for water remains the availability of the resource itself, increasing concentrations of wastewater-derived contaminants and more impaired water quality may serve as an omen of what scientists and regulators might expect in areas predicted to have decreased precipitation and surface water flow as a result of global climate change. Moreover, the increasing trend in source water concentrations highlight the need for a better understanding of what risk, if any, pharmaceuticals and EDCs pose to drinking water and aquatic ecosystems.

References

Barnett, T., R. Malone, W. Pennell, D. Stammer, B. Semtner, and W. Washington. 2004. The effects of climate change on water resources in the West: Introduction and overview. Clim. Change 62(1–3):1–11.

Barnett, T. P. and D. W. Pierce. 2008. When will Lake Mead go dry? Water Resources Res. 44(3).

Barnett, T.P., D.W. Pierce, H.G. Hidalgo, C. Bonfils, B.D. Santer, T. Das, G. Bala, A.W. Wood, T. Nozawa, A.A. Mirin, D.R. Cayan, and M.D. Dettinger. 2008. Human-induced changes in the hydrology of the western United States. Science (Washington, DC) 319(5866):1080–1083.

Benotti, M.J., R.A. Trenholm, B.J. Vanderford, J.C. Holady, B.D. Stanford, and S.A. Snyder. 2009. Pharmaceuticals and endocrine disrupting compounds in U.S. drinking water. Environ. Sci. Technol. 43(3):597–603.

Brikowski, T.H. 2008. Doomed reservoirs in Kansas, USA? Climate change and groundwater mining on the Great Plains lead to unsustainable surface water storage. J. Hydrol. 354(1–4):90–101.

Daughton, C.G., and T.A. Ternes. 1999. Pharmaceuticals and personal care products in the environment: Agents of subtle change? Environ. Health Perspect. 107:907–938.

Donn, J., M. Mendoza and J. Pritchard. 2008. Pharmaceuticals found in drinking water, affecting wildlife and maybe humans. The Associated Press. 9 Mar. 2008.

Glassmeyer, S.T., E.T. Furlong, D.W. Kolpin, J.D. Cahill, S.D. Zaugg, S.L. Werner, M.T. Meyer, and D.D. Kryak. 2005. Transport of chemical and microbial compounds from known wastewater discharges: Potential for use as indicators of human fecal contamination. Environ. Sci. Technol. 39(14):5157–5169.

Jones, O.A., J.N. Lester, and N. Voulvoulis. 2005. Pharmaceuticals: A threat to drinking water? Trends Biotechnol. 23(4):163–167.

Kolpin, D.W., E.T. Furlong, M.T. Meyer, E.M. Thurman, S.D. Zaugg, L.B. Barber, and H.T. Buxton. 2002. Pharmaceuticals, hormones, and other organic wastewater contaminants in U.S. streams, 1999–2000: A national reconnaissance. Environ. Sci. Technol. 36(6):1202–1211.

Kuehn, B.M. 2008. Traces of drugs found in drinking water: Health effects unknown, safer disposal urged. J. Am. Med. Assoc. 299(17):2011–2013.

LaBounty, J.F., and N.M. Burns. 2005. Characterization of Boulder Basin, Lake Mead, Nevada-Arizona, USA-Based on analysis of 34 limnological parameters. Lake Reservoir Manage. 21(3):277–307.

McCabe, G. J. and D. M. Wolock (2007). Warming may create substantial water supply shortages in the Colorado River Basin. Geophysical Research Letters 34(L22708).

Routledge, E.J., D. Sheahan, C. Desbrow, G.C. Brighty, M. Waldock, and J.P. Sumpter. 1998. Identification of estrogenic chemicals in Stw effluent. 2. In vivo responses in trout and roach. Environ. Sci. Technol. 32(11):1559–1565.

Snyder, E.M., S.A. Snyder, K.L. Kelly, T.S. Gross, D.L. Villeneuve, S.D. Fitzgerald, S.A. Villalobos, and J.P. Giesy. 2004. Reproductive responses of common carp (*Cyprinus Carpio*) exposed in cages to influent of the Las Vegas Wash in Lake Mead, Nevada, from late winter to early spring. Environ. Sci. Technol. 38(23):6385–6395.

Snyder, S.A., T.L. Keith, D.A. Verbrugge, E.M. Snyder, T.S. Gross, K. Kannan, and J.P. Giesy. 1999. Analytical methods for detection of selected estrogenic compounds in aqueous mixtures. Environ. Sci. Technol. 33(16):2814–2820.

Snyder, S.A., R.A. Trenholm, R.C. Pleus, G.M. Bruce, E.M. Snyder, E. Bennett, and J.C.D. Hemming. (2008). Toxicological relevance of Edcs and pharmaceuticals in drinking water. AwwaRF no. 3085. Awwa Res. Foundation and WateReuse Foundation, Denver, CO.

Snyder, S.A., E.C. Wert, D.J. Rexing, R.E. Zegers, and D.D. Drury. 2006. Ozone oxidation of endocrine disruptors and pharmaceuticals in surface water and wastewater. Ozone-Sci. Eng. 28(6):445–460.

Snyder, S.A., P. Westerhoff, Y. Yoon, and D.L. Sedlak. 2003. Pharmaceuticals, personal care products, and endocrine disruptors in water: Implications for the water industry. Environ. Eng. Sci. 20(5):449–469.

Trenholm, R.A., B.J. Vanderford, J.C. Holady, D.J. Rexing, and S.A. Snyder. 2006. Broad range analysis of endocrine disruptors and pharmaceuticals using gas chromatography and liquid chromatography tandem mass spectrometry. Chemosphere 65(11):1990–1998.

UNESCO. 2006. Water, a shared responsibility. United Nations Educational, Scientific and Cultural Organization, Paris.

USBOR. 2009. Drought in the Upper Colorado River Basin. Available at http://www.usbr.gov/uc/feature/drought.html (verified 9 Oct. 2009). U.S. Bureau of Reclamation, Washington, DC.

USEPA. 2005. Unregulated contaminant monitoring program. U.S. Environ. Protection Agency, Washington, DC.

USGS. (2004). Climatic fluctuations, drought, and flow in the Colorado River Basin. USGS Fact Sheet 2004–3062 version 2. U.S. Dep. of the Interior, U.S. Geol. Surv., Reston, VA.

Vanderford, B.J., R.A. Pearson, D.J. Rexing, and S.A. Snyder. 2003. Analysis of endocrine disruptors, pharmaceuticals, and personal care products in water using liquid chromatography/tandem mass spectrometry. Anal. Chem. 75(22):6265–6274.

Vanderford, B.J., and S.A. Snyder. 2006. Analysis of pharmaceuticals in water by isotope dilution liquid chromatography/tandem mass spectrometry. Environ. Sci. Technol. 40(23):7312–7320.