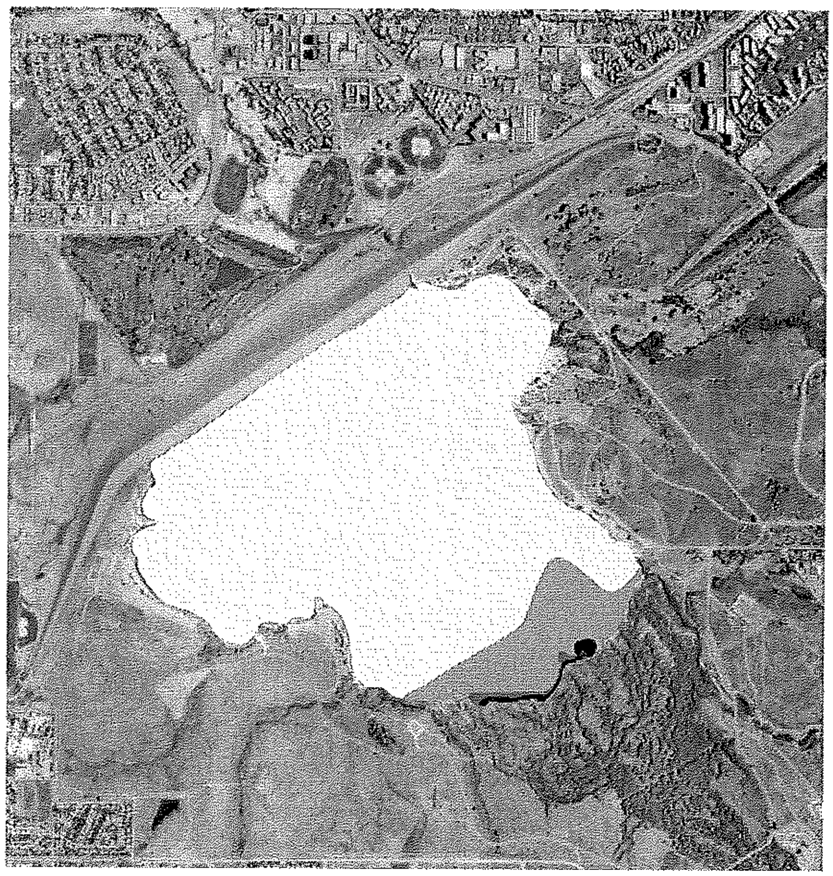
Estimation of Groundwater Flow into Cherry Creek Reservoir and its Relationship to the Phosphorus Budget of the Reservoir



Prepared by:
William M. Lewis, Jr.
James H. McCutchan, Jr.
James F. Saunders, III

Supported by:
Cherry Creek Basin Authority
Colorado Department of
Public Health and Environment

February 9, 2005

Rpt219

Executive Summary

Estimates were made of seepage contributions to Cherry Creek Reservoir by direct measurement methods and by mass-balance analysis of conservative ions. Direct measurements showed that seepage occurs primarily in shallow water between Cherry Creek and Cottonwood Creek over an area of approximately .036 km^2 (90 acres) as shown by use of seepage meters and piezometers. A zone of very intensive seepage occupies approximately 5700 m^2 (1.5 acres) within this seepage zone. In addition, seepage occurs in the wetland just above the lake shore where Cherry Creek and Cottonwood Creek enter the reservoir. Seepage in this area, which totals about 1.1 km^2 (275 acres), was assumed to be the same as the mean for all measured rates within the submerged seepage zone at the lake edge. Total seepage, as estimated by these methods, was 2235 acre-feet per year. A separate estimate obtained through the application of mass-balance principles based on the differences in chemical composition of alluvial ground water and tributary runoff was 2255 acre-feet per year. Both of the estimates in these studies confirm a water-budget analysis based on USACE and Chatfield Basin Authority data indicating that seepage is about 2200 acre-feet per year (about 20% of tributary flow). The study also shows that no significant amounts of flow leave the basin by seepage.

The seepage load of phosphorus to the reservoir is 530 kg (1170 lbs), or about 50% as high as the point-source allocation for the reservoir; it is a previously unquantified component of phosphorus load to the reservoir. The seepage load is of phosphorus about 8% of the maximum annual load recognized by the State of Colorado.

Because inorganic nitrogen passing through the groundwater system shows pronounced loss of nitrogen through denitrification, the entry of seepage water contributes to a bias in the N/P ratio favoring phosphorus. This is part of the explanation for Cherry Creek Reservoir's low N/P ratio, which favors the development of nitrogen-fixing bluegreen algae.

Introduction

The Cherry Creek Reservoir Control Regulation, which was adopted by the Colorado Water Quality Control Commission at the recommendation of the Colorado Department of Public Health and Environment, has the purpose of curtailing excessive nutrient enrichment of Cherry Creek Reservoir. The main basis for the regulation is interception of phosphorus within the watershed as a means of preventing excessive algal growth in the reservoir.

Consistent with the Cherry Creek Reservoir Control Regulation, the Cherry Creek Basin Authority and the Colorado Department of Public Health and Environment Water Quality Control Division approved for the year 2004 a study of the rate of entry of groundwater into Cherry Creek Reservoir and an accompanying quantification of the amount of phosphorus that enters the reservoir by this mechanism. This study was motivated by the knowledge that a substantial amount of groundwater passes beyond the upper end of the reservoir within the alluvium. While some of the subsurface flow passes beneath the Cherry Creek Dam and appears in Cherry Creek below the dam, it has not been clear whether a significant portion of the water enters the reservoir as well. If so, unmeasured phosphorus loading of the reservoir could occur as a result.

The purpose of the groundwater seepage study, results of which are described here, is to estimate the contribution of seepage water and its load of phosphorus to Cherry Creek Reservoir. The study is based on application of two methods that provide independent indications of seepage: (1) empirical measurement of seepage rates by use of seepage meters and analysis of seepage water; (2) mass-balance analysis based on passive tracers involving groundwater. The results of these two aspects of the study are reported, and general conclusions are then drawn from the two parts of the study.

Direct Studies of Seepage

Seepage was studied directly in three ways: (1) determination of ice thickness over shallow water during winter; (2) use of piezometers and sediment sampling to make synoptic studies of seepage potential over the entire lake; and (3) use of seepage meters to measure seepage rate and collect seepage samples for analysis

Methods

Substantial amounts of seepage in shallow water can be expected to cause thinning of ice cover because ground water is much warmer than lake water during winter. Therefore, inspection of the perimeter of the lake during a period of ice cover is one means of detecting areas of abundant seepage.

Inspection of the perimeter of the lake during January and February 2004 showed that ice cover ranged between 200 – 300 mm (8 – 12 inches) for the most part. In one location approximately one third the distance between the inlets of Cherry Creek and Cottonwood Creek at the southeastern end of the reservoir, the ice thickness was much less (50 – 100 mm, or 2 - 4 inches). In fact, ice was completely absent from this area over much of the winter and the temperature of the water often exceeded 4 ° C. Therefore, the observations indicated that a substantial amount of seepage was probably occurring between Cherry Creek and Cottonwood Creek along the southeastern shore of the lake. This area was subsequently sampled extensively with seepage meters, and will be referred to here as the "high seepage area."

In early 2004, while ice still covered most of the lake, samples were taken at 81 locations on ten dates near the shore of the lake and within tributaries. The samples were collected with piezometers from a depth below the sediment surface of about 40 cm (screen depth 30-50 cm). A few samples also were collected from a greater depth (60 cm; screen depth 50-70 cm). Prior to collection of a sample from a piezometer, several volumes were pumped through the piezometer (the piezometer was pumped dry if hydraulic conductivity of the sediment was low). The pore water sampled in this way was analyzed for specific conductance. Measurements of specific conductance, as well as dissolved oxygen, temperature, and pH also were taken of water overlying the sediment at the same site, and samples were taken of the overlying water. The samples of pore water and of overlying water were filtered within 12 hours of collection (Whatman GF/C filters) and were frozen pending further analysis. The water samples were then analyzed as follows: ammonium (Grasshoff 1976), total dissolved phosphorus (Lagler and Hendricks 1982, Valderrama 1981), anions (chloride, sulfate, bromide, fluoride, and nitrate) by ion chromatography, and cations (calcium, magnesium, sodium and potassium) by ICP-MS. Some locations yielded insufficient pore water for analysis.

During March 2004, 81 sediment samples were collected over a grid covering the entire lake (spacing about 200 m). The surface sediments (upper 10 cm) were collected with a ponar grab or piston coring device. Additional samples were collected along two transects over the high seepage area. Sediment samples from the survey were analyzed gravimetrically for water content, organic matter, and carbonate. High organic and water content of sediment usually indicates that entry of seepage water is unlikely.

Seepage rates were measured with seepage meters similar to those described by Lee (1977). The meters were 250 mm in diameter and were connected to polyethylene bags with 16-mm tubing. A total of 60 estimates of seepage rate were made over 12 sampling intervals ranging from 1-8 days, depending on the rate of seepage accumulation in the bags. The measurements were made between January and November of 2004. The measurements were concentrated in shallow water along the southeastern portion of the lake, where other sampling indicated the greatest potential for seepage.

Results

The use of piezometers showed that sediments in shallow water varied substantially in hydraulic conductivity (as indicated by the speed with which tubes filled with water after being pumped). Near the mouth of Cottonwood Creek, hydraulic conductivity was low, indicating little possibility for seepage. Hydraulic conductivity also was low on the western edge of the lake to the south of the marina and on the eastern edge of the lake south of the swim beach. Also, at most locations more than 20 m from the shore hydraulic conductivity was so low that pore water could not be collected. In the high-seepage area, pore water was readily collected up to 100 m from shore. Specific conductance of pore water was lowest in the high seepage area (Figure 1). Pore water with conductance lower than surface tributary water is an indication of seepage. A few locations along the northernmost shore, to the east of the dam, showed low specific conductance, but most other samples of pore water had higher conductance (greater than 950 μS/cm). Concentrations of a number of major ions in pore water (pumped from piezometers) showed anomalies in spatial distribution reflecting groundwater influence in the high seepage area (Appendix I). Sulfate and nitrate in pore water showed evidence of loss through redox transformation in transit to the high seepage area.

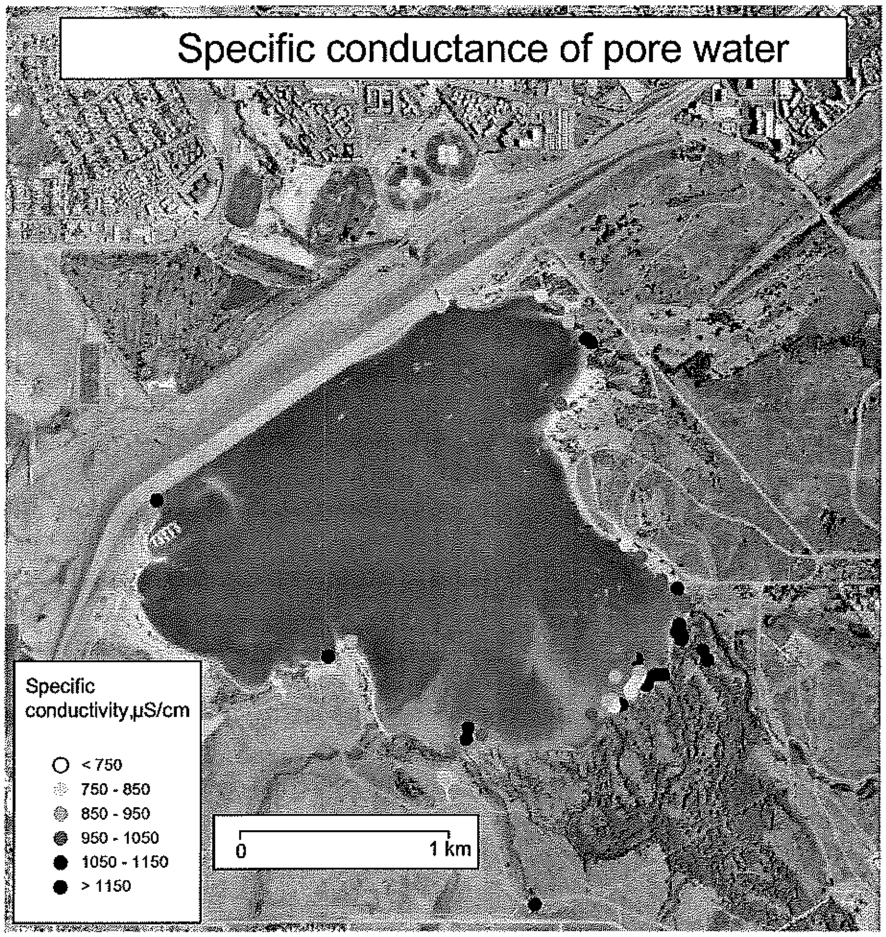


Figure 1.

In early 2004, when samples of pore water were collected, most of the lake was covered with ice. Because ice cover prevents mixing of the lake water by wind, chemical signatures should be detectible not only in pore water, but also in overlying water if rates of groundwater seepage are high. For the high-seepage area, spatial patterns of specific conductance for overlying water resembled those of pore water. Samples of overlying water from the high-seepage had low conductance as compared with overlying water from other areas. Concentrations of specific solutes in overlying water, reflecting groundwater influence, typically were lower in the high-seepage area than in other areas of the lake. Concentrations of total dissolved phosphorus (TDP), however, were higher (for both pore water and overlying water) in the high-seepage area than elsewhere, as would be expected from the high concentrations of TDP in alluvial wells (ca. 190 µg/L in wells).

The survey of lake sediments showed similar spatial patterns for water content, organic content, and carbonate content (Figures 2-4). Sediments from the middle of the lake had high water content and also high concentrations of organic matter and carbonate. Sediments of coarse sand with high hydraulic conductivity (i.e., sediments with low water content and low amounts of organic matter and carbonate) were found only along the margin of the lake and were concentrated in two areas: 1) near the swim beach and 2) in the high-seepage area. Sediments near the swim beach were underlain by clay, probably because the sand from the beach now covers the original clay substrate; the underlying clay would be expected to block seepage.

Estimates of seepage rate that were made with seepage meters were highly variable spatially (range, <0.1 mm/d to > 50 mm/d: mean of all measurements = 6.2 mm/d; median = 2.2 mm/d). The highest rates of seepage were observed in the high-seepage area, but not all of the estimates for this area were high and rates often varied substantially for locations less than 20 m apart (Figure 5). There was no indication that rates of seepage varied seasonally (Tukey Kramer HSD, $q^* = 3.39$, $p > 0.05$), although weak seasonality could have been masked by spatial variability in rates of seepage.

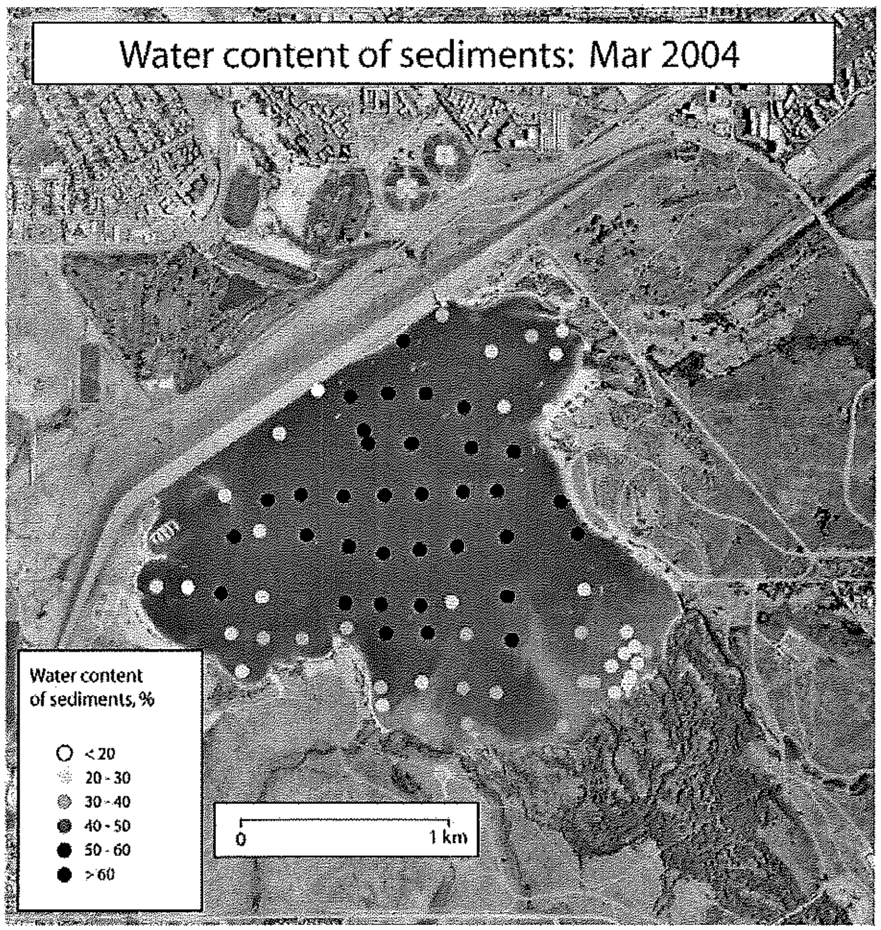


Figure 2.

Over much of the lake, hydraulic conductivity (as estimated qualitatively when samples of pore water were collected and from organic content and water content of sediments) was sufficiently low that significant rates of groundwater seepage would not have been possible. The survey of lake sediments showed higher hydraulic conductivity in the high-seepage area than in most other parts of the lake. The potential for high rates particularly in the high-seepage area was confirmed by direct estimates of seepage rate with seepage meters.

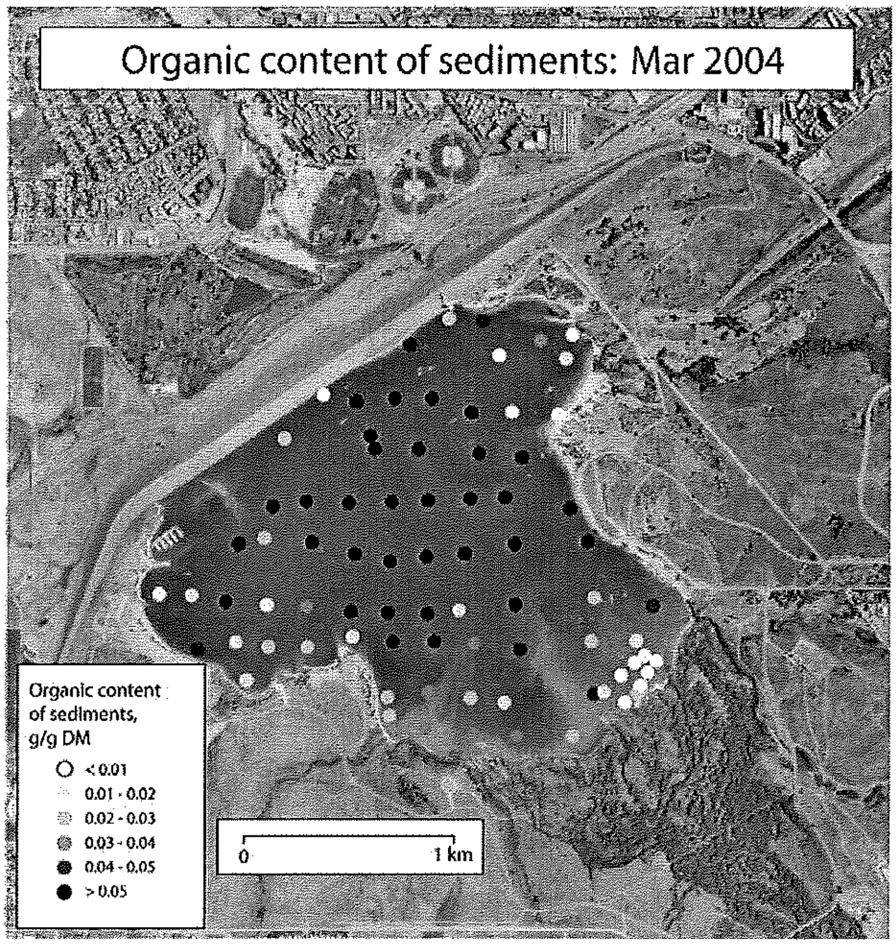


Figure 3.

Seepage calculations for the lake (Table 1, Figure 5) are based on quantitative estimates for the high-seepage areas.

Although not quantified in this study, seepage of alluvial water occurs in the wetland southeast of the lake, between Cherry Creek and Cottonwood Creek. The area of the wetland is approximately three times the area relevant to seepage calculations for the lake (Table 1), but the average rate of seepage for the wetland is unknown.

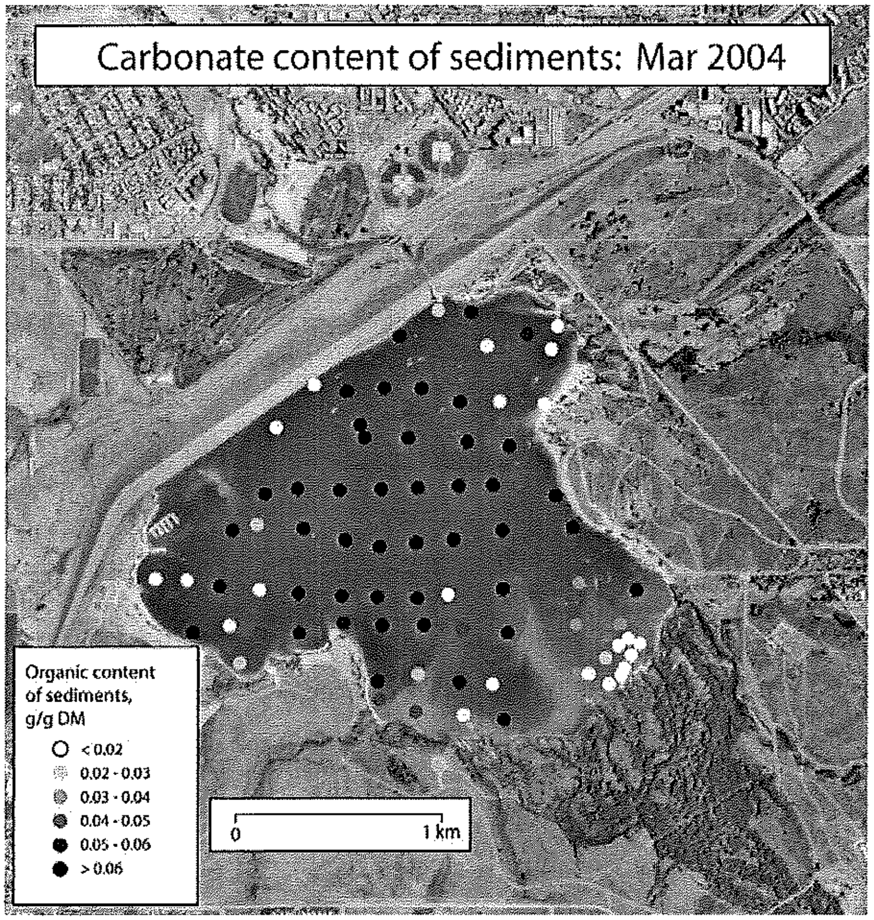


Figure 4.

A provisional estimate is set equal to the mean for all seepage rate measurements (6 mm/d). Results are shown in Table 1 (an area-weighted mean would show total half as large as what is shown in Table 1).

Nutrient loading caused by groundwater seepage directly to the lake can be calculated from the concentrations of total dissolved phosphorus (TDP), dissolved inorganic nitrogen (DIN; nitrate plus ammonia), and the rate of seepage to the lake. Concentrations of TDP averaged 118 μg/L in the high-seepage area. This concentration incorporates some dilution associated with lake water that enters the collection bag when the meter is

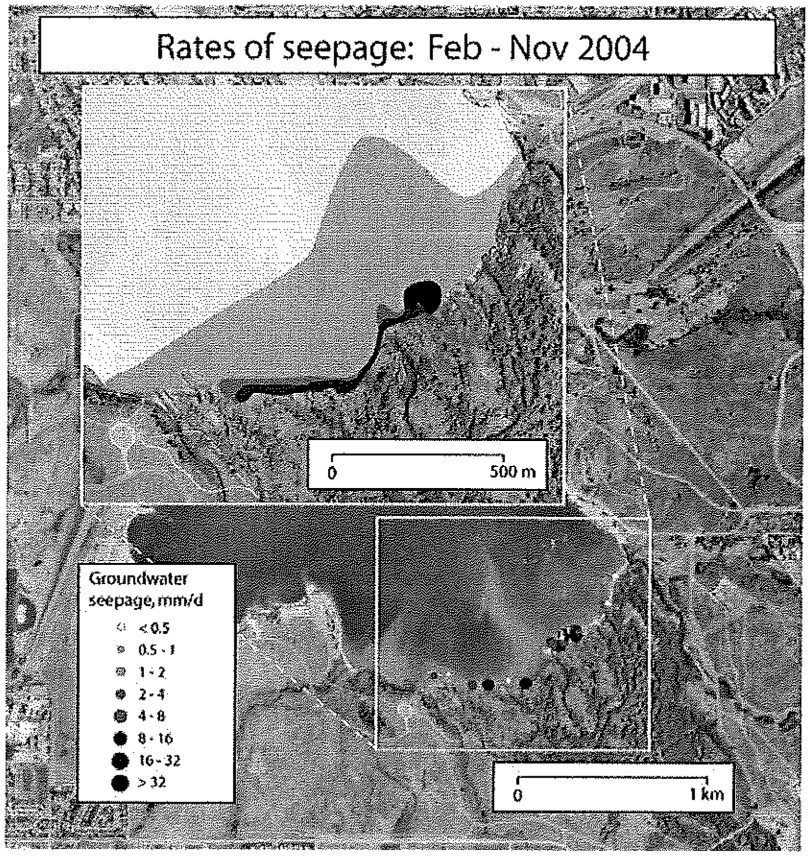


Figure 5.

installed. Therefore, the concentration of TDP in undiluted seepage was assumed to be set equal to that of the nearest alluvial well (MW9, mean 190 µg/L in 2004). Concentrations of DIN were much lower (50 µg/L) in the high-seepage area than in the alluvial well (788 µg/L); this large difference in concentration suggests that most of the inorganic nitrogen in the alluvial water is lost through denitrification before entering the lake as seepage. A similar fraction of the nitrogen in the alluvial water may be lost en route through the wetland; this is assumed to occur but this assumption is speculative. Based on concentrations for DIN in wetland seepage equal to those for lake seepage and of seepage rates and areas as shown in Table 1, groundwater loading of phosphorus and nitrogen can be calculated (Table 2).

Rate of seepage	Area, m^2	Seepage, L/s	Seepage, cfs	Seepage, Acre-feet/y
Lake Bottom (measured, mm/d)				
64	5655	4.19	0.148	107
16	15660	2.90	0.102	74
4	12830	0.59	0.021	15
1	327000	3.78	0.134	97
Total	361000	11.46	0.405	293
Wetland *				
6	1,094,000	75.3	2.64	1942
Grand Total	1,455,000	86.8	3.04	2235

* No direct measurements; estimated only from lake seepage (see text).

Table 1. Summary of seepage calculations for Cherry Creek Reservoir.

		Concentration μg/L	Transport kg/y
Lake Bottom			
	P	190	69
	N	50	18
Wetland (rough estimate)			
	P	190	455
	N	50	120
Total			
	P	190	524
	N	50	137

Table 2. Transport of P and inorganic N to the lake by seepage.

Indirect Estimates of Seepage: Use of Mass Balance

If the chemistry of the lake is documented, and the chemistry and amount of inflowing water at the surface are known, the amount of inflowing alluvial water can be estimated from the difference between the chemistry of the water in the lake and the chemistry of the water entering the lake at the surface. This principle is applied here to Cherry Creek Reservoir.

Water Balance for the Reservoir

It is possible to estimate seepage for years in which all surface inflows are monitored, as was the case for water years 1992 – 1997 (Chatfield Basin Authority, annual reports). The median difference between all inflows (including precipitation), and all outflows (including evaporation), is 2220 acre-feet per year, or about 3 cfs. Thus, if the flow monitoring was reasonably accurate, this would be an expected value for seepage as determined from the analysis of mass balance for dissolved substances.

Mass balance for water during year 2004, the year of the study reported here, is shown in Table 3, with the mean annual seepage estimated from 1992-1997 hydrology added to complete the estimate.

Inflow/outflow	Amount in acre-feet
USACE computed inflow	14539
Precipitation*	985
Surface inflow	13554
Estimated Seepage	2220
Estimated Tributary flows	11334

*The precipitation record was incomplete for May – July: these months were estimated.

Table 3. Water budget for the year of study (2004), assuming that seepage is 2220 acre-feet per year, as determined by water balances for the years 1992-1997.

Chemistry of Seepage Water

The specific conductance and ionic content of seepage water consistently is below the specific conductance of lake water or surface water in tributaries. Plots relating volume of water trapped in the seepage meters during 2004 versus conductance or cation concentrations show a decline toward an asymptote at high seepage volumes because the seepage meters trap a small amount of lake water when they are deployed. As seepage volume accumulates, the initial lakewater contamination becomes a progressively less important component of the whole, as shown by movement toward an asymptotic of concentration. Samples from bags showing ionic concentration near the asymptote were assumed to contain minimally contaminated seepage water, and were used for the mass-balance analysis as representing uncontaminated seepage. The cation concentrations of water from these seepage meters correspond to concentratons observed in well MW9, which is closest to Cherry Creek. The concentrations of the four major cations (calcium, magnesium, sodium, and potassium) were used in mass-balance analysis.

Tributary Contributions

Three tributaries were considered: Cherry Creek, Cottonwood Creek, and Shop Creek. Data were collected on the cation content of these sources during 2004. The discharge-weighted averages for each cation, corrected for net evaporation from the lake, would equal the concentrations of cations in the lake at the end of the year in the absence of seepage, given that hydraulic residence time is about one year. Deviation from these averages is explained by seepage.

Results of the discharge-weighted averaging process for the four major cations are shown in Table 4. In addition, the table summarizes the information on the concentrations of these four ions in alluvial water obtained from seepage collectors with minimal lakewater contamination. The final column in the table shows annual seepage as estimated separately from data on each of the four ions. The median of these estimates can be taken as the best-available overall estimate based on mass balance. This best-available estimate is quite close to estimated alluvial inflow as obtained from water-balance analysis.

Conclusion

As a result of the studies done in 2004 and analysis of water-budget data from the USACE and Chatfield Basin Authority, three separate estimates are available for seepage entering the reservoir (Table 5). The three estimates agree surprisingly well, indicating that the annual seepage is very close to 2200 acre-feet per year, including seepage that surfaces near the lake shore between Cherry Creek and Cottonwood Creek as well as seepage that surfaces within the wetland but beyond the point where flow of Cherry Creek is measured. Seepage is about 20% of surface inflow through tributaries.

	Concentration, mg/L			Seepage, Estimated
Ion	Seepage*	Tributaries**	Lake***	Acre-feet/year
Ca^{++}	93.1	67.0	80.3	2200
Mg^{++}	14.0	14.9	17.4	2860
Na^{+}	51.0	73.5	77.4	1880
K^{+}	4.35	6.90	7.35	2310
Median	--	--	--	2255

*From seepage meters.
**Flow-weighted mean of the tributaries, 2004.
***At the outlet tower in November, 2004.

Table 4. Summary of data and calculations of seepage by use of mass balance.

Source	Amount of Seepage acre-feet/year
Water budget	2220
Direct seepage measurements*	2235
Seepage estimate based on mass balance	2255

* Includes wetland seepage, which was estimated indirectly with a low degree of uncertainty.

Table 5. Summary of seepage estimates.

The phosphorus loading associated with seepage is about 530 kg/year, which is 50% as high as the point-source allocation for the reservoir and consititutes a previously unquantified addition to the total phosphorus load of the reservoir. The seepage load is about 8% of the maximum annual phosphorus load recognized by the State of Colorado.

Because inorganic nitrogen passing through the groundwater system shows pronounced loss of nitrogen through denitrification, the entry of seepage water contributes to a bias in the N/P ratio favoring phosphorus. This is part of the explanation for the low N/P ratio, which favors the development of nitrogen-fixing bluegreen algae.

References

Grasshoff, K. 1976. Methods of seawater analysis. Verlag Chimie, Weinheim.

Lagler, C. L. and P. F. Hendrix. 1982. Evaluation of persulfate digestion method for particulate nitrogen and phosphorus. Water Research 16: 1451-1451.

Lee, D. R. 1977. A device for measuring seepage flux in lakes and estuaries: Limnology and Oceanography 22, 140-148.

Valderrama, J. C. 1981. The simultaneous analysis of total nitrogen and phosphorus in Natural Waters. Marine Chemistry 10: 109-122.