Freshwater Biology (2003) **48**, 1219–1231

Coupled biogeochemical and hydrological responses of streams and rivers to drought

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SUMMARY

1. Severe or extreme droughts occurred about 10% of the time over a 105-year record from central New Mexico, U.S.A., based on the Palmer Drought Severity Index.
2. Drought lowers water tables, creating extensive areas of groundwater recharge and fragmenting reaches of streams and rivers. Deeper groundwater inputs predominate as sources of surface flows during drought. Nutrient inputs to streams and rivers reflect the biogeochemistry of regional ground waters with longer subsurface residence times.
3. Inputs of bioavailable dissolved organic carbon to surface waters decrease during drought, with labile carbon limitation of microbial metabolism a byproduct of drought conditions.
4. Decreased inputs of organic forms of carbon, nitrogen and phosphorus and a decrease in the organic : inorganic ratio of nutrient inputs favours autotrophs over heterotrophs during drought.
5. The fate of autotrophic production during drought will be strongly influenced by the structure of the aquatic food web within impacted sites.

Keywords: biogeochemistry, dissolved organic carbon, drought, hydrology, nutrient cycling, surface water/groundwater interactions, water table

Introduction

Lake (2000) pointed out that droughts have been greatly neglected by aquatic ecologists. Drought also is a multifaceted term that is not easily defined. Droughts commonly develop slowly, but often do more economic damage than any other type of natural disaster (National Research Council, 1999). Droughts normally do not have distinct beginnings, but they usually have sharp ends. Hydrological effects of droughts include reduced runoff, soil moisture, groundwater levels and discharge. Palmer (1965) defined meteorological drought as 'an interval of time, generally of the order of months or years in duration during which the actual moisture supply at a given place rather consistently falls short of the climatically appropriate moisture supply.' A somewhat shorter definition is that drought is an unusually long period with little or no precipitation.

There are many indices used to indicate drought (Heim, 2002; Keyantash & Dracup, 2002). Commonly used indices include (1) percentage of normal precipitation, (2) standardised precipitation index, (3) Palmer Drought Severity Index (PDSI), (4) crop moisture index, (5) Surface Water Supply Index (SWSI), (6) reclamation drought index, and (7) deciles (http://www.enso.unl.edu/ndmc/enigma/indices.htm). Indices based on percentage of normal precipitation, standardised precipitation index and deciles rely on different methods to assess precipitation over varying periods of time relative to long-term climate records in a region. The crop moisture index is a derivative of the PDSI that reflects moisture supply in the short term across crop-producing regions. It is not intended to assess droughts in the long term. The SWSI was developed for use where mountain snowpack is a key element of water supply. The reclamation drought index incorporates precipitation, snowpack, stream flow, reservoir levels

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and temperature into the index. The PDSI was the first comprehensive drought index developed in the US (Palmer, 1965) and both historical (http://www.ncdc.noaa.gov/onlineprod/drought/main.html) and weekly maps (http://www.nic.fb4.noaa.gov/products/analysis_monitoring/regional_monitoring/palmer.gif) are available via the Internet. Two modifications of the PDSI also are commonly used. These include the Palmer Hydrological Drought Index (PHDI) and the Palmer Modified Drought Index (PMDI). The availability of the PDSI, PHDI and PMDI back to 1895 throughout the US makes these indices valuable for examining the pattern, timing and severity of droughts throughout the last century in the US.

The effects of drought on the biogeochemistry of streams and rivers are less thoroughly documented than the effects of floods. Few studies have discussed the impacts of droughts on stream and river chemistry (Williams & Melack, 1997; Wall, Phillips & Riva-Murray, 1998; Morecroft *et al.*, 2000), but the majority of papers that consider drought, focus on biogeochemical responses when drought ends (Foster & Walling, 1978; Bayley *et al.*, 1992). Documented impacts of drought on stream and river biogeochemistry include reduced silica concentrations (Williams & Melack, 1997; Wall *et al.*, 1998), acid neutralising capacity (Williams & Melack, 1997), and nitrate (Morecroft *et al.*, 2000). Cessation of drought brings a major flush of solutes to surface waters. In particular, concentrations of nitrate increase several times when drought ends (Foster & Walling, 1978; Reynolds & Edwards, 1995; Morecroft *et al.*, 2000).

Drought has a major impact on the interface between ground waters and surface waters (Boissier *et al.*, 1996; Dahm *et al.*, 1998). Declining water tables during drought affect (1) the direction and volume of water exchanged between surface waters and ground waters, (2) sources and chemistry of water within surface flow, and (3) redox potential and chemistry of alluvial ground waters. Vertical hydraulic gradient (VHG), a measure of the pressure differential between surface waters and ground waters, becomes increasingly negative, indicating surface water recharge of ground waters along stream reaches as drought develops (Henry *et al.*, 1994; Valett *et al.*, 1994; Wroblicky *et al.*, 1998). Surface flows during drought rely increasingly on deep ground waters with longer residence times and greater equilibration with aquifer lithology (Hornberger *et al.*, 1998). Redox potential of the shallow alluvial aquifer decreases as a result of hypoxia or anoxia as groundwater flows are increasingly directed away or parallel to the channel and recharge of the aquifer from the floodplain or upland declines (Wroblicky *et al.*, 1998; Baker, Dahm & Valett, 2000b; Baker, Valett & Dahm, 2000a).

Declining water tables during drought also influence the extent of the alluvial aquifer that is saturated in stream and river floodplains (Baker *et al.*, 2000a). This critical interface between aquatic and terrestrial ecosystems affects organic carbon dynamics within the catchment, and carbon limitation of groundwater metabolism often occurs during low flow conditions (Baker *et al.*, 2000a). Metabolic processes at this interface affect the availability of dissolved oxygen, the distribution of aerobic and anaerobic microbial processes, and concentrations of redox sensitive solutes (e.g. ammonium, nitrate, ferrous iron, manganous manganese, sulphate, sulphide and methane). Aerobic processes in the unsaturated zone above the falling water table produce nitrate, sulphate and dissolved organic carbon (DOC) available for mobilisation and transport to surface waters when a drought ends. Drought both affects the biogeochemistry of surface waters and alluvial ground waters and sets the stage for biogeochemical changes to surface waters when drought ends.

The aims of this paper are to (1) describe the long-term pattern of drought occurrences for a large catchment in the western United States using the PDSI, (2) document water table responses from moderate to severe drought in a small stream and large river within this catchment, (3) characterise hydrological characteristics of interactions of ground waters and surface waters during drought, and (4) present some biogeochemical responses of shallow alluvial ground waters and stream surface waters during drought. Drought indices will be examined for the Rio Grande basin of central New Mexico, U.S.A., with more detailed studies of hydrology and biogeochemistry focused upon Rio Calaveras, a first order tributary within the basin.

Methods

Site descriptions of Rio Calaveras and Rio Grande

Rio Calaveras is a first order, perennial, spring-fed stream in the Jemez Mountains, New Mexico, U.S.A.

(35°56′N, 106°42′W). Rio Calaveras is a tributary of the Rio Grande at an altitude of 2475 m and draining a catchment of 37.6 km^2. The catchment is a mixed conifer forest with a relatively open stream canopy, with limited overstory riparian vegetation. Stream discharge ranges from <0.001 $\text{m}^3\ \text{s}^{-1}$ during times of drought to >0.1 $\text{m}^3\ \text{s}^{-1}$ during periods of rapid snowmelt. Mean annual precipitation is 450 mm, with rain predominating during monsoon thunderstorms from July to September and snow during November–March. Alluvium ranges in size from poorly sorted gravels to medium-grain sands derived from tuff of volcanic origin.

The Rio Grande at Bosque del Apache National Wildlife Refuge, New Mexico, U.S.A. (33°40′N, 106°59′W), drains a semi-arid to arid catchment of 70 900 km^2. The altitude of the river at the refuge is approximately 1390 m. The refuge includes over 19 km of meandering Rio Grande channel and associated riparian vegetation. Riparian vegetation includes both native cottonwood-dominated forests (*Populus deltoides* var. *wislizenii* (S. Wats.) Eckenwalder) and exotic saltcedar-dominated forests (*Tamarix chinensis* Lour.). Discharge for the Rio Grande at Bosque del Apache has ranged from no measurable surface discharge during severe droughts to >570 $\text{m}^3\ \text{s}^{-1}$ during major floods. Peak discharge historically occurred during mountain snowmelt in May and June, but extensive flow regulation of the river has largely removed the flood peak. Minimal flows resulting from drought, evapotranspiration (ET) and anthropogenic depletions normally occur in late summer or fall. Shallow alluvium along the Rio Grande is predominantly sand at depth with a greater percentage of finer textured soils near the surface.

Drought indices

A long-term record of the PDSI, PHDI and PMDI was obtained from the National Climatic Data Center of the United States for the period from 1895 to 2000 (http://www.ncdc.noaa.gov/onlineprod/drought/main.html) on a monthly basis. The Palmer Index varies roughly between −6.0 and +6.0. The PDSI was originally described in Palmer (1965) and the limitations and assumptions of the PDSI are described in detail by Alley (1984). The PDSI is probably the most widely used drought index and the basis of the method is a water balance calculation using precipitation and temperature data. The method takes into account precipitation, ET and soil moisture conditions. Assumptions in the PDSI calculations include the accuracy of computing potential evapotranspiration (PE), ET equaling PE when monthly precipitations exceeds PE and the approach used to estimate runoff (Alley, 1984). The PDSI, PHDI and PMDI were analysed for region 2 of New Mexico, U.S.A. Region 2 corresponds to the north central part of New Mexico and includes the region where most of the hydrological and biogeochemical measurements were made.

Hydrology

Discharge from Rio Calaveras was measured with a Palmer-Bowlus plastic flume (Plasti-Fab Inc., Tualatin, OR, USA). The flume was located at the end of a 120-m reach of stream and flood plain into which numerous groundwater sampling wells have been installed (Valett *et al.*, 1996; Morrice *et al.*, 1997; Valett *et al.*, 1997; Wroblicky *et al.*, 1998; Baker, Dahm & Valett, 1999; Baker *et al.*, 2000b). All wells were constructed of 5-cm inner diameter polyvinyl chloride (PVC) pipe with 50-cm screen lengths capped on the bottom. Wells were installed 30–50 cm below the baseflow water table. Water table elevations were recorded with a battery-operated water level meter that detects changes in specific conductivity. Mini-piezometers (*sensu* Lee & Cherry, 1978) were used to characterise ground water/surface water exchange (Henry *et al.*, 1994). The mini-piezometers consisted of 60-cm lengths of open-ended PVC pipe (1.25 cm inner diameter) installed to a depth of 30 cm beneath the streambed. Water inside the mini-piezometer equilibrates at a level reflecting pressure in the subsurface environment. If subsurface pressure is greater than surface pressure, subsurface water enters the mini-piezometer and equilibrates some distance above the stream surface. If atmospheric pressure is greater than subsurface pressure at 30 cm depth, then water levels are below the water surface. VHG is a unitless ratio relating the difference in hydraulic head above or below the stream surface to the depth of the mini-piezometer into the sediment. Positive values indicate upwelling or groundwater discharge zones and negative values indicate downwelling or groundwater recharge zones. Surface discharge from the Rio Grande was measured at US Geological Survey gauge at San Marcial just south of the Bosque del Apache National

Wildlife Refuge and at the Otowi gauge northwest of Santa Fe, New Mexico, U.S.A. The Otowi Bridge gauge has a 105-year record of discharge back to 1895. PVC wells of the same size used at Rio Calaveras were installed 100 cm below the baseflow water table and screened over a 100 cm length in the riparian zone at the Rio Grande site at Bosque del Apache. Well sites were located approximately 200 m inland of the active channel. Five wells were installed in the riparian zone of the Bosque del Apache site. Continuous monitoring of pressure transducers were deployed in 1999 and 2000 to measure water table elevations in Rio Grande wells with measurements taken every 30 min.

Biogeochemistry

Groundwater samples were obtained using a bailer or peristaltic pump with in-line Whatman GF/F glass-microfiber filters (average pore size 0.7 μm, Whatman, Maidstone, UK) to remove suspended particles. Surface water samples were collected after repeated rinsing of the sample bottles and filtered upon return to the laboratory. Filtered samples were stored in acid-washed polyethylene bottles on ice until they were returned to the laboratory for analyses. Nitrate (NO_3^-) was measured using a DIONEX-500 ion chromatograph (DIONEX, Sunnyvale, CA, USA) with suppressed conductivity detection (Chapelle & Bradley, 1996). Phosphate (PO_4^{3-}) was measured on an autoanalyser using the colorimetric method of Murphy & Riley (1962). DOC was determined using wet persulphate oxidation (100 °C) on an Oceanography International 700 total carbon analyzer (Oceanography International, College Station, TX, USA) (Menzel & Vacarro, 1964).

Results

The PDSI from 1895 to 2000 for region 2 of New Mexico, where the two study sites are located, shows two periods of extended drought during the period of record (Fig. 1). The periods from 1899 to 1904 and 1950 to 1956 are long-term droughts. Short-term droughts occur throughout the record with the first half of 1996 and most of 2000 in drought conditions. The PDSI, PHDI and PMDI provide comparable long-term characterisation of drought in this region (Table 1). Indices between −2.0 and −2.99 are classified as moderate drought, −3.0 and −3.99 as severe drought and <−4.0 as extreme drought. The three Palmer indices classified 46–48 months (3.6–3.8%) of the 1272-month record as extreme drought, 78–87 months (6.1–6.8%) of the record as severe drought and 126–150 months (9.9–11.8%) as moderate drought. Both the 1996 and 2000 droughts reached values indicative of severe drought, while the 2000 drought reached values indicative of extreme drought by these indices (Fig. 2). Furthermore, the strength of the droughts in 1996 and 2000 was classified in the same category by each of the three indices. Both the 1996 and 2000 droughts greatly diminished spring flow of the Rio Grande at Otowi Bridge (Fig. 3). Flows during spring snowmelt did not exceed 50 $m^3\ s^{-1}$ in 1996 and 2000, while the long-term average spring snowmelt discharge is almost 150 $m^3\ s^{-1}$.

Water table elevations for the growing seasons of 1999 and 2000 are shown in Fig. 4 for a well in the riparian zone of the Bosque del Apache site along the Rio Grande. Severe or extreme drought has a marked effect on the depth to ground water in alluvial flood plains. Drought in 2000, which reached the severe category in the PDSI in May, dropped the water table nearly 2 m in June 2000 compared with June 1999 in riparian wells along the Rio Grande (Fig. 4). Water table depths continued to decline throughout the growing season until early August. Water table elevations showed two distinct peaks in 1999 associated with strong summer monsoonal precipitation. The gradual increase in the water table in August 2000 was not the result of summer monsoonal precipitation. In fact, the PDSI reached extreme drought levels in August and September 2000 (Fig. 2). Drying of the river in the Bosque del Apache region generated legal challenges to protect an endangered fish species, the Rio Grande silvery minnow (*Hybognathus amarus* Girard), and court-ordered flow augmentation from upstream reservoirs produced the water table rise in August 2000. Daily ET of the dense thicket of saltcedar (*Tamarix chinensis*) at the site produced the diurnal change in elevation seen in the growing season of both years. The water table rise in October of 1999 and 2000 reflected both the cessation of riparian ET and the end of the irrigation season.

Water table fluctuations at Rio Calaveras also clearly show the impacts of drought on alluvial ground waters (Fig. 5). Peak discharge commonly occurs in late April or May as a result of spring snowmelt. The period from 1995 to 1997 included a strong snowmelt year in 1995 (peak discharge 0.102 $m^3\ s^{-1}$), a drought year in 1996 (peak discharge

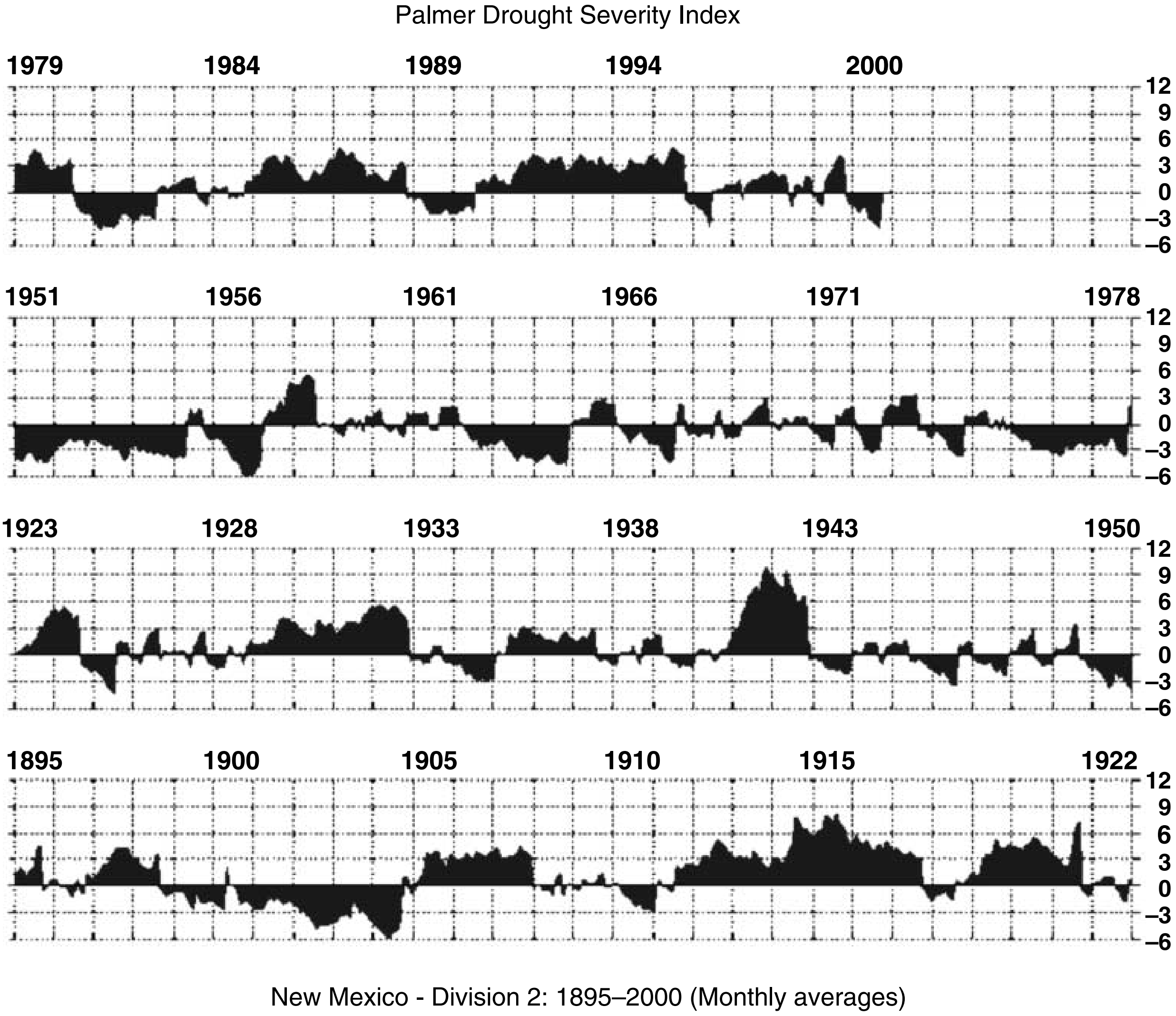

Fig. 1 Monthly averages of the Palmer Drought Severity Index (PDSI) for region 2 of New Mexico, U.S.A., from 1895 to 2000.

$0.0018\ m^3\ s^{-1}$), and a moderate snowmelt year in 1997 (peak discharge $0.0308\ m^3\ s^{-1}$) (Fig. 5a). Wells in the flood plain within 3 m of the active channel (Fig. 5b) and in the floodplain >3 m from the channel (Fig. 5c) both showed the effects of drought. Water table drops of almost 40 cm occurred between 1995 and 1996 in wells within 3 m of the channel and about 70 cm for wells further out into the flood plain.

Table 1 Number of months and percentage of months in parentheses that fall within various drought categories for the Palmer Drought Severity Index (PDSI), the Palmer Hydrologic Drought Index (PHDI) and the Palmer Modified Drought Index (PMDI). The table is based on records from a total of 1272 months from 1895 to 2000

Drought category	Index range for drought category	PDSI	PHDI	PMDI
Moderate	<–2.00–2.99	130 (10.2)	150 (11.8)	126 (9.9)
Severe	<–3.00–3.99	79 (6.2)	87 (6.8)	78 (6.1)
Extreme	<–4.00	46 (3.6)	48 (3.8)	47 (3.7)

Patterns of VHG in the channel of Rio Calaveras also strongly showed the impact of drought (Fig. 6). Positive VHGs dominated along a 150-m reach of the stream in June 1995 with values reaching +0.6. The direction of flow was overwhelmingly from ground water to surface water (discharge) and the reach gained water in June 1995. Negative VHGs dominated along the same reach of stream in the drought year of 1996 with values reaching −0.6. The direction of flow was strongly from surface water to ground water

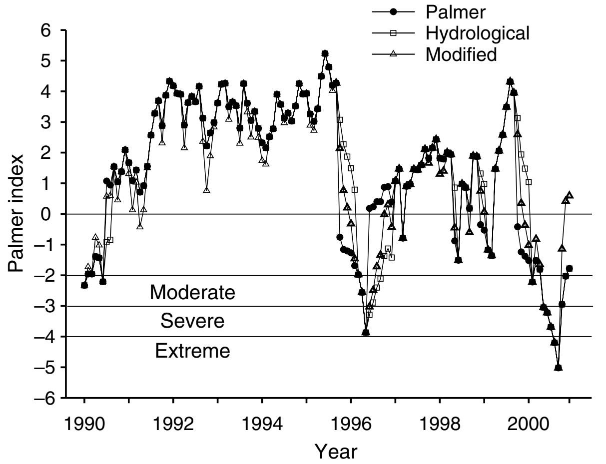

Fig. 2 Palmer Drought Severity Index (PDSI), Palmer Hydrological Drought Index (PHDI) and Palmer Modified Drought Index (PMDI) for region 2 of New Mexico, U.S.A., from 1990 to 2000.

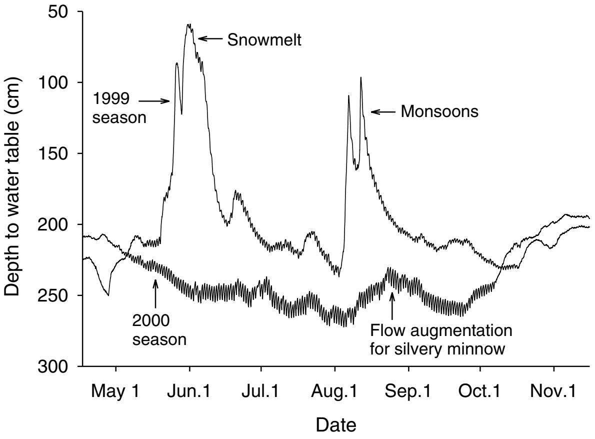

Fig. 4 Water table elevations in depth to ground water for the growing seasons of 1999 and 2000 at Bosque del Apache in a saltcedar-dominated riparian zone along the Rio Grande, New Mexico, U.S.A.

(recharge) and the reach lost water in June 1996. The direction of flow and source of surface waters changed from years of moderate to high discharge when compared with drought years.

Biogeochemical characteristics of surface waters and ground waters at Rio Calaveras also were very responsive to drought. The concentrations of DOC in surface waters were elevated throughout most of the period of snowmelt-affected discharge in 1995 while DOC concentrations remained low and relatively invariant during the drought period of 1996 (Fig. 7). Concentrations of DOC exceeded 7.0 mg L^{-1} in spring 1995, but never exceeded 2.6 mg L^{-1} in the period of drought in 1996. Similarly, there was a distinct increase of surface water nitrate concentrations at the early stages of snowmelt in 1995, which was absent in the spring of 1996 (Fig. 8). Concentrations of stream water nitrate decrease throughout late spring in both years when benthic algal production was high. Differences in the concentration of phosphate between years were not strong (Fig. 9). Concentrations decreased during periods of strong benthic algal growth, but differences in stream water phosphate concentrations between drought years and years of higher discharge were not apparent.

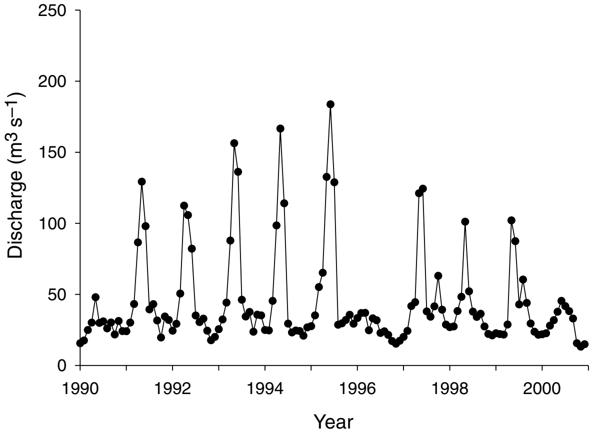

Fig. 3 Discharge at the Otowi Bridge gauge station on the Rio Grande, U.S.A., from 1990 to 2000.

Discussion

Drought is a subtle weather phenomenon with very real impact that does more economic damage than floods and hurricanes (Svoboda *et al.*, 2002). Accurate indices that diagnose the onset and severity of drought have been sought for decades. Michael Hayes (http://www.enso.unl.edu/ndmc/enigma/indices.htm), a climate impact specialist with the US National Drought Mitigation Center (NDMC), discusses various indices presently in use in the US and Australia. Seven indices (Percentage of Normal, Standardised Precipitation Index, PDSI, Crop Moisture Index, SWSI, Reclamation Drought Index and Deciles) are commonly used in the U.S. and Australia. Australians use deciles, developed by Gibbs & Maher (1967), where groups of monthly precipitation are compared with

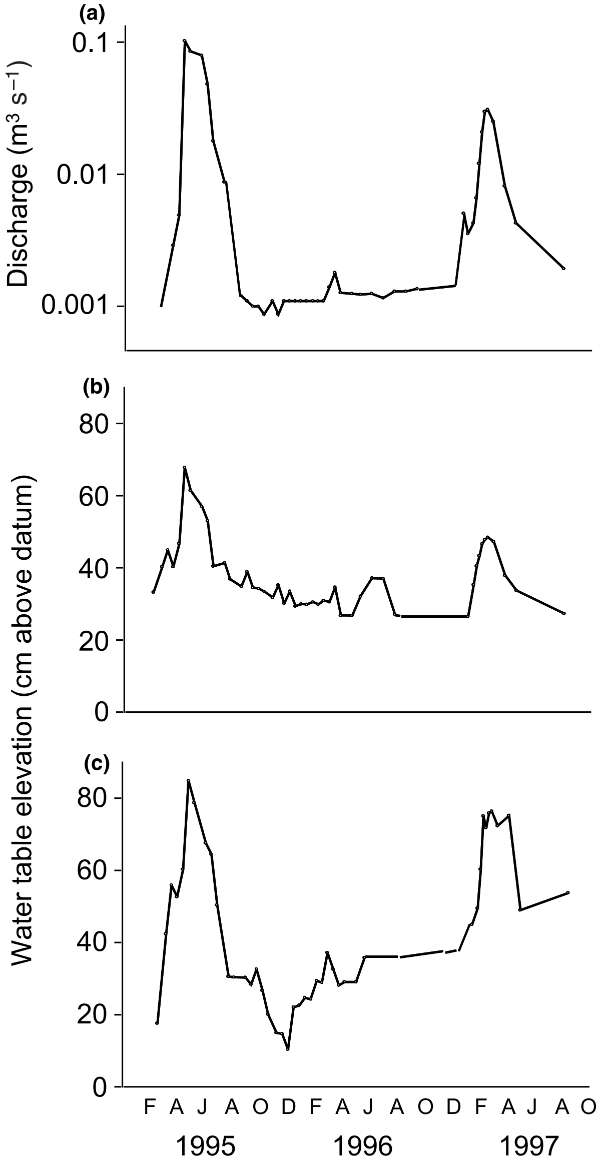

Fig. 5 Water table fluctuations from interface wells and floodplain wells and surface discharge at Rio Calaveras, New Mexico, U.S.A., from 1995 to 1997 (modified from Baker *et al.*, 2000b). Panel a shows discharge, panel b shows groundwater wells within 3 m of the active channel, and panel c shows floodplain wells >3 m from the active channel.

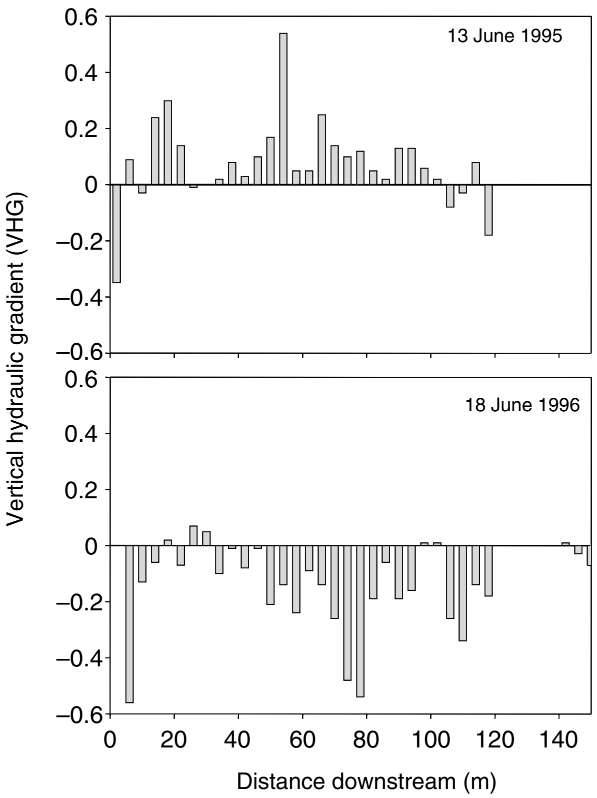

Fig. 6 Patterns of vertical hydraulic gradient (VHG) for a 150-m reach of stream at Rio Calaveras in June 1995, a strong snowmelt year, and June 1996, a drought year.

the long-term climatic data record of the region. Advantages of this index are ease of calculation with fewer assumptions and less data requirements than the PDSI. The main disadvantage of the decile system is that a long climatological record is required. The US NDMC uses a newer index, the Standardised Precipitation Index, to monitor soil moisture supplies, because it identifies emerging drought sooner than the PDSI. The PDSI (Palmer, 1965) and related indices (PHDI and PMDI), however, remain widely used and a long-term record exists (from 1895 to the present) for the entire US. Alley (1984) describes strengths and weaknesses of the PDSI. Weaknesses include lags in Palmer values during emerging droughts, applicability in mountainous landscapes, and suitability in areas of frequent climatic extremes. The PDSI and related indices are used in this paper as they allow a long-term examination of drought in the region where linked hydrological and biogeochemical studies have been conducted.

Droughts are common in the southwestern region of North America with approximately 20% of months since 1895 classified as moderate to extreme drought (Table 1). The droughts of 1996 and 2000 were of short duration compared with stronger, long-term droughts earlier in the century. Extended droughts occurred in region 2 of New Mexico from 1899 to 1904 and 1950 to 1956. The 1950s drought is considered the most

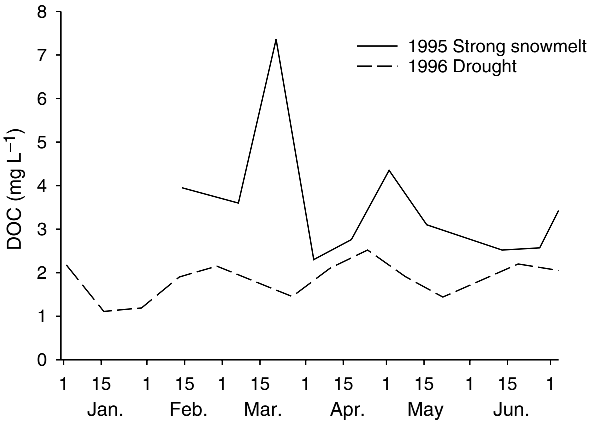

Fig. 7 Concentrations of dissolved organic carbon in surface waters at Rio Calaveras for the period of January 1995 to June 1995, a strong snowmelt year, and for the period of January 1996 to June 1996, a drought year.

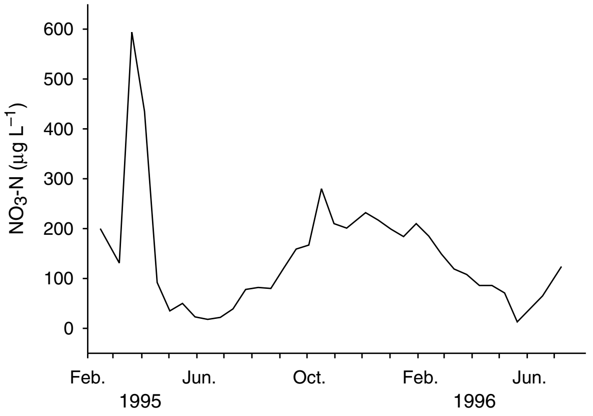

Fig. 8 Concentrations of nitrate in surface waters at Rio Calaveras from 1995 to summer 1996.

extreme drought in the past 500 years, based on tree ring data (Swetnam & Betancourt, 1998; Swetnam, Allen & Betancourt, 1999). During this drought, extensive changes in terrestrial vegetation throughout the region have been documented (Betancourt *et al.*, 1993). Although the droughts of 1996 and 2000 were of much shorter duration, the severity of each reached either extreme drought (1996) or severe drought (2000) categories as classified by the PDSI, PHDI and PMDI.

Extreme or severe drought affects the relative contribution of water derived from the main pathways by which precipitation ultimately can be discharged into a stream or river channel. Four main flow paths are: (1) direct precipitation, (2) overland flow, (3) shallow subsurface flow, and (4) groundwater flow (Hornberger *et al.*, 1998). During periods of drought, inputs of direct precipitation, overland flow and shallow subsurface flow decrease and deeper groundwater flows sustain surface flows (Freeze, 1972). Declining alluvial groundwater tables during drought reverse the direction of flow between surface waters and ground waters over much of stream and river reaches. Biogeochemical characteristics of surface waters during drought reflect low-nutrient conditions of deeper ground waters of the catchment.

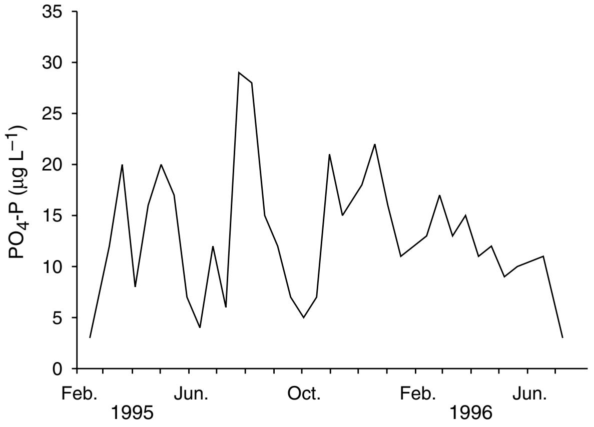

Fig. 9 Concentrations of phosphate in surface waters at Rio Calaveras from 1995 to summer 1996.

One distinct biogeochemical response of streams and alluvial ground waters to drought is decreased concentrations of DOC. Hornberger, Bencala & McKnight (1994) describe hydrological controls on DOC concentrations during snowmelt in montane streams. DOC in near-surface soils beneath the snowpack, built up because of microbial activity, is released during spring snowmelt (Boyer *et al.*, 1997). Baker *et al.* (2000b) showed that DOC concentrations increased 1–2 mg L^{-1} above mean baseflow concentrations in alluvial ground waters at Rio Calaveras during the period immediately before peak stream discharge in the 2 years without drought. Concentrations of DOC in alluvial ground waters, however, did not increase significantly during the drought in 1996, suggesting that drought greatly attenuates this flush of DOC into ground waters and surface waters. Baker *et al.* (2000b) also found that microbial metabolism in alluvial ground waters was limited by the availability of labile DOC during baseflow but was not DOC limited during snowmelt. Energy supplies to streams and rivers in the form of DOC are much reduced during times of drought.

Freeman *et al.* (1994) showed that summer drought stimulates autotrophy in a stream draining a peatland. Bacterial population densities, however, were not significantly affected. The increase in autotrophy was attributed to a decrease in the organic : inorganic ratio of nutrients entering the stream. The decrease in DOC inputs into Rio Calaveras during drought probably was also accompanied by decreased groundwater inputs of dissolved organic nitrogen (DON) and dissolved organic phosphorus (DOP) and an overall decrease in the organic : inorganic ratio of nutrient inputs into surface waters. We did not measure DON and DOP concentrations in surface and ground waters at Rio Calaveras, but we predict that DON and DOP concentrations would have decreased similarly to DOC concentrations. Overall, we hypothesise that decreased DOC inputs, decreased organic : inorganic ratios of nutrient inputs and increased autotrophy (on an area basis) is a general effect of drought on streams and rivers.

Drought also affects the delivery of nitrate to surface waters. Normally, the rising limb of the hydrograph during snowmelt or major precipitation events brings increased concentrations of nitrate (Foster & Walling, 1978; Reynolds & Edwards, 1995; Morecroft *et al.*, 2000; Peterson, Valett & Dahm, 2001). Drought in the spring of 1996 at Rio Calaveras substantively attenuated the spring flush of nitrate into the stream. Changes in the benthic algal community during the drought included (1) decreased cell biovolume, (2) decreased algal density, and (3) decreased percentage of live diatoms (Peterson *et al.*, 2001). Decreased nutrient availability and increased invertebrate grazing were suggested as mechanisms producing these shifts (Peterson *et al.*, 2001). Soluble reactive phosphorus was not clearly affected by the drought in spring 1996, but decreasing inorganic N : P ratios in stream water favoured nitrogen-fixing cyanobacteria over diatoms and chlorophytes during this period of drought.

Research on the effects of drying on nutrient dynamics and algal succession at Sycamore Creek, Arizona, U.S.A., also provides insights on the effects of drought on stream ecosystems (Grimm, 1987; Peterson & Grimm, 1992; Holmes, Fisher & Grimm, 1994; Valett *et al.*, 1994; Stanley, Fisher & Grimm, 1997). Extended periods of dryness in this desert stream result in less surface water habitat and distinct points of groundwater discharge controlled by attributes of stream geomorphology. The remaining discharge locations for ground water during times of drought are enriched in nitrate in this nitrogen-limited stream ecosystem. Algal community structure and productivity are very responsive to these discharge zones with rapid uptake and utilisation of nitrate inputs near the points of groundwater discharge. Nitrogen depletion leads to the predominance of nitrogen-fixing cyanobacteria, or diatoms with nitrogen-fixing cyanobacterial symbionts, throughout much of the wetter stream channel (Peterson & Grimm, 1992).

Drought also affects the availability of inorganic nutrients in surface waters through influences on nutrient retention (Valett *et al.*, 1996; Morrice *et al.*, 1997; Mulholland *et al.*, 1997). Nutrient inputs during drought become patchy, occurring only at discrete locations where deeper sources of ground water continue to discharge into surface waters (Dent & Grimm, 1999). Discharge decreases during drought and advective velocities decrease, which can lead to decreased nitrate uptake lengths (Morrice *et al.*, 1997). Williams & Melack (1997) and Wall *et al.* (1998) report declines in the concentration of dissolved silica during drought. These declines could be a result of enhanced retention of silica by benthic diatoms rather than a decrease in the concentration of groundwater silica entering the channel. Increased retention of nutrients within a reach of stream or river during drought increases the chance that nutrient limitations will occur downstream of locations of groundwater discharge.

A conceptual model of the effects of drought on the hydrology and biogeochemistry of the interface between surface waters and ground waters is shown in Fig. 10. Groundwater discharge sustains stream flow under baseflow conditions, a dominant condition temporally in streams and rivers (Hynes, 1983). Sources of ground water include inputs from the shallow alluvial aquifer and deeper regional sources. Water table elevations with respect to water levels in the channel drive transport of shallow ground waters to and from the active channel along alluvial corridors. Inputs are spatially heterogeneous along stream reaches with inputs of nutrients and organic matter exchanging between surface and ground waters. When drought conditions develop, the connectivity

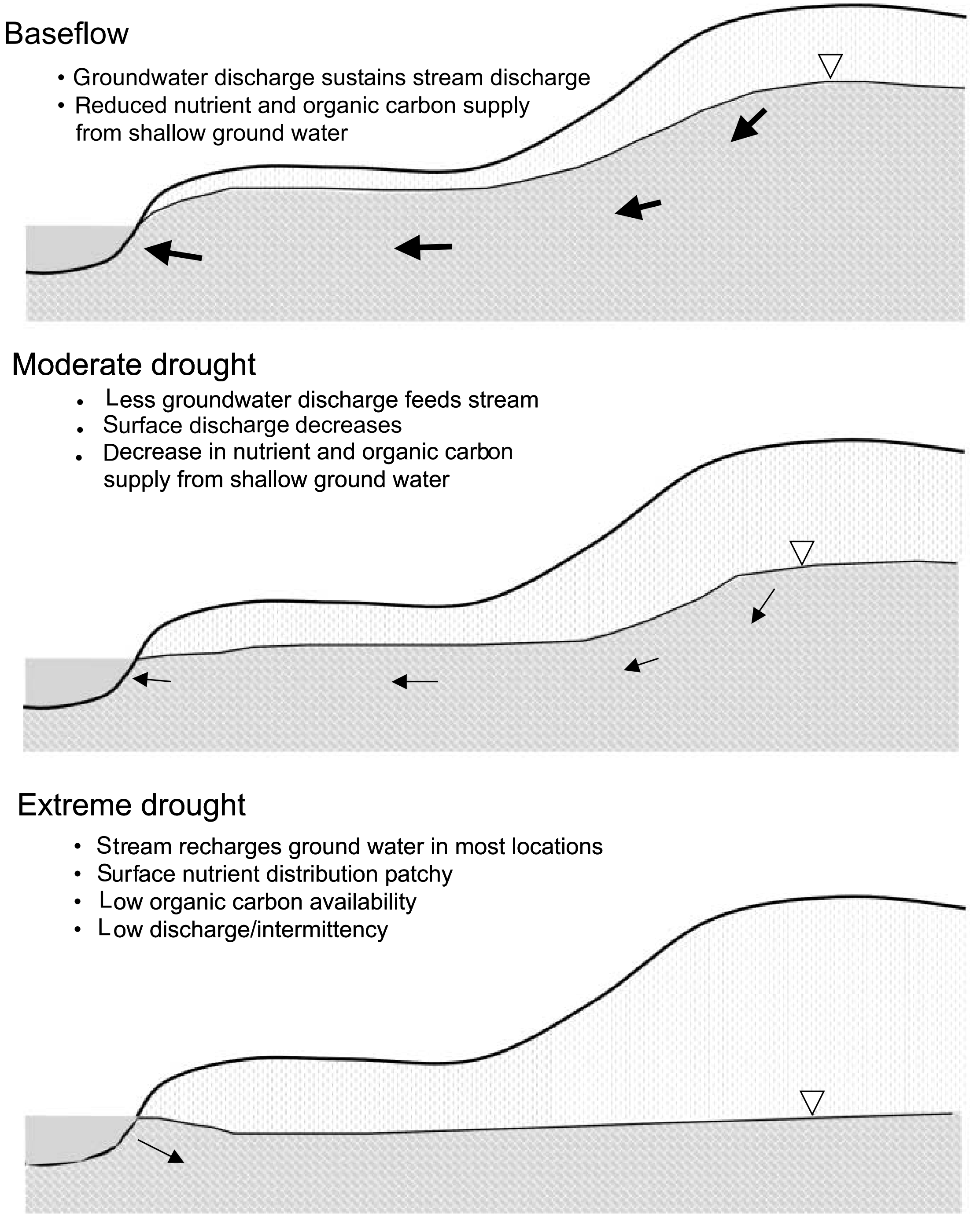

Fig. 10 Conceptual representation of increasing drought intensity on interactions between surface waters and ground waters and stream biogeochemistry.

between alluvial ground waters of the adjacent floodplain diminishes. Plant transpiration in the riparian zone draws down the alluvial water table, increasing the movement of water and solutes from the channel to the alluvial aquifer (Fig. 4). Inputs of inorganic nutrients and labile sources of DOC from the adjacent floodplain are much decreased as shallow groundwater sources are depleted. Surface discharge decreases and stream biogeochemistry increasingly reflects the characteristics of the deeper regional aquifer.

Older water with longer residence times in the subsurface makes up increasing amounts of the remaining surface flow (Hornberger *et al.*, 1998). When extreme drought develops, the stream becomes largely groundwater recharging and most reaches lose surface water. Intermittency occurs in many regions worldwide, with the length of active stream channel and the surface area of wetted channel much reduced. Biogeochemical characteristics of surface waters are strongly influenced by parent lithology, the geochemistry of regional aquifers, and biogeochemical processes occurring over decadal or longer time periods in the regional ground waters that sustain limited flow during extreme droughts. Labile sources of organic matter are depleted in this older ground water, while inorganic nutrients reflect characteristics of regional aquifers with longer water residency times (Baker *et al.*, 2000a). Allochthonous sources of DOC and other forms of organic nutrients such as organic nitrogen and phosphorous are much reduced and autotrophic processes are enhanced relative to heterotrophic processes within remaining surface waters.

The interplay between drought, nutrient availability and food chain interactions is expected to be complex. Drought brings about a decrease in discharge, generally lower nutrient availability and contracted aquatic habitat in streams and rivers. From a biogeochemical perspective, the contracting size of aquatic habitats and discrete nature of groundwater discharge points during drought, decrease overall inputs of nutrients and focuses nutrient inputs to distinct locations along the stream or river continuum. Stable temperatures, clear water and decreased ratios of organic : inorganic forms of nitrogen and phosphorus are more likely to favour high rates of autotrophic production at these locations (Freeman *et al.*, 1994; Peterson *et al.*, 2001). Increased productivity by benthic algae, however, can enhance herbivory by aquatic invertebrates, which can occur in higher densities during drought because of contracting space and limited physical disturbance (Peterson *et al.*, 2001). Grazing insects can substantially lower standing crops of algae and rates of primary production. Predation from insectivorous fish or invertebrates, however, can strongly influence rates of primary production and algal biomass through food chain interactions that regulate numbers and species of grazing invertebrates (Power, 1990, 1992). Both top–down and bottom–up effects will inevitably exert strong influences on streams and rivers during drought. Biogeochemical and food-web effects require careful consideration and research as we seek a better understanding of the role of drought on stream and river ecosystems.

Acknowledgments

The authors thank the many members of the Hydrogeoecology Group at the University of New Mexico, past and present, for their help with field and laboratory work. This research was funded by grants from the U.S. National Science Foundation (DEB 9420510, DEB 9816087, DEB 9903973, DEB 0080529, and EAR 0083752) and the U.S. National Aeronautics and Space Administration (NASA) through contract NAG5-6999. This paper is publication 184 from the Sevilleta LTER Project.

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(Manuscript accepted 8 April 2003)