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ARTICLE

Simulation of Water Level Fluctuations in Kettle Holes Using a Time Series Model

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Abstract Kettle holes are widespread in moraine landscapes. Their hydrological properties may be very vulnerable to changes in climatic conditions. To increase our knowledge of how kettle holes function and how they may be affected by climate change requires a model that can be applied to a variety of them regardless of their properties. We used the PIRFICT time series model to simulate the water levels in kettle holes over the last 50 years. For model calibration we applied time series of two-year lengths. We observed correlations between climate indices and water level statistics with a delayed response of one year. The results show a decrease in autumn low water levels and an increase in water level fluctuations. These effects correspond to observed increased summer evaporation and winter precipitation, and imply that the habitat quality dynamic of kettle holes depends on climatic conditions. With the prognosis of even warmer and dryer summers in Europe in the future, conservation strategies for kettle holes should include the effects of climate change.

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Introduction

In north-eastern Germany kettle holes are widely distributed, occurring with densities of up to 40 per km² over an area of 38,000 km², which results in total numbers of between 150,000 and 300,000 (Klafs and Lippert 2000). The origin of many of them is not clear. Edvardsen and Okland (2006) group such small eutrophic ponds into three classes: those with a natural origin resulting from special geological conditions, those originating mostly from agricultural activities, or those that have been constructed. Although it is a well known fact that kettle holes are important features of agricultural landscapes and that they are essential for some plant and animal species (Gibbs 1993), knowledge of their functioning is still fragmentary (Kalettka 1996), and more than 50% have been lost in north-eastern Germany over the last century (Klafs and Lippert 2000). This number is comparable with the wetland loss in the United States (Dahl 1990; Johnston 1994), Japan (Shimoda 1997), Denmark (Moller and Rordam 1985), and the United Kingdom (Wood et al. 2003). Despite national protection and private wetland conservation efforts, they are still decreasing in number and area (Mouser et al. 2005). A decreasing number of kettle holes may increase the risk of isolation of local plant and animal populations resulting in a higher species extinction risk (Moller and Rordam 1985; Dodd 1990; Sjogren 1991). Restoration of kettle holes is therefore an important part of overall conservation efforts and should include studies of their spatial and temporal variability to understand the natural conditions of these landscape features (Biggs et al. 2005).

Studies focusing on processes in kettle holes have recently proliferated (Schneeweiß 1996; Gibbs 2000) but research dealing with the spatial and temporal variability of kettle holes' environmental characteristics is still very rare (Pyke 2004; de Meester et al. 2005; Kalettka and Rudat 2006). Hydrological research on kettle holes focused, either process-orientated (Pyzoha et al. 2008; Johnson et al. 2009; Voldseth et al. 2009) or descriptive (Gamble and Mitsch 2009; Kahara et al. 2009; Skalbeck et al. 2009; Sumner et al. 2009), on a limited number of study sites. Further, most ecological studies ignore the link between species occurrence and habitat dynamics of kettle holes (Luthardt and Dreger 1996; Schneeweiß 1996). So far, we have found only one hydrological model that deals with the spatial and temporal variability of ponds (Pyke 2004), but this model can be applied only to ponds lacking an interaction with ground water. Furthermore, it requires information about properties that are unique to each pond, properties that therefore have to be ascertained before applying the model. To meet the needs for kettle-hole protection a hydrological model is required that can be applied to all kinds of kettle holes, given limited knowledge of their properties.

Regardless of their origin, most kettle holes are situated on low permeable sediments (Dempster et al. 2006), limiting downward percolation. As a result, precipitation stagnates and creates a perched water table. Kettle holes are fed by precipitation and/or seepage from the surrounding perched aquifer and lose water by evaporation (Pierce 1993) and drainage into the surrounding soil or regional ground-water system (Woo and Rowsell 1993; Ferone and Devito 2004). The hydrology of kettle holes is thus influenced mainly by meso-scale climatic conditions (Poiani and Johnson 1991; Ferone and Devito 2004) and varies considerably among years.

Modelling water balance and hydrological dynamics of kettle holes typically requires knowledge of their hydrogeological properties as well as climatic inputs (Larson 1995; Moorhead 2003). Properties such as catchment area, soil permeability, and vegetation structure are unique to each kettle hole and define its dynamic response, but these properties may not be easy to identify (Lissey 1971) and can even vary over time (Chorley 1978). Hence, the high variability of pond properties and the surrounding environmental conditions limit the application of mechanistic hydrological models to the majority of kettle holes.

In this study, we applied the time series model PIRFICT (Predefined Impulse Response Function In Continuous Time) (von Asmuth et al. 2002) to a set of 17 kettle holes in north-eastern Germany. The resulting time series of daily water depth can be used to calculate statistics on seasonal and inter-seasonal variability and risks of drought or overflow of kettle holes. With these statistics we were able to describe the hydrological variability and could show how the hydrology of kettle holes depends on climate.

Methods

Study Area

In order to cover a wide range of hydrological characteristics in kettle holes within heterogeneous landscapes, the geological map of Mecklenburg Western Pomerania (LUNG 2005) and a map of kettle hole density by Klafs and Lippert (2000) were used. The study area, a central part of Mecklenburg Western Pomerania (Fig. 1), represented a good balance between morphological diversity and pond density.

The study area was situated on the terminal moraine of the Pomeranian Staffel of the glacial Weichsel Period and extended over an area of approximately 10 km². A glacial outburst intersected the terminal moraine and formed the lower part of the study area. It was characterized by fine sandy depressions with scattered ponds, lakes, and wet meadows of different sizes. In the terminal moraine, pond bed sediments were dominated by clay and silt lenses underlain by sandy materials. Pond size varied from 0.01 to 0.5 ha. Because of the geomorphological and size differences of the examined kettle holes, the hydrological dynamics of each pond were expected to vary. Seventeen out of 46 total kettle holes in the area were randomly selected as research locations and their water levels were monitored on a daily basis in 2002 from May until November and in 2003 from April until October, using automatic data logging probes (PDLA70, ecoTech, Bonn, Germany (eco-Tech 2002)).

Time Series Analysis

From a system identification or signal analysis point of view (Ljung 1999), the water level dynamics in a pond reflect the dynamics of the inputs into the system. The transformation of model input to model output (the water level) is described by a simple transfer function. In this case the model inputs, i.e., daily precipitation and potential evaporation, were received from the nearest weather station at Schwerin (DWD 2004), 60 km west of study area.

Model Background

To describe the response of the water level to precipitation, the PIRFICT model uses the Pearson type III

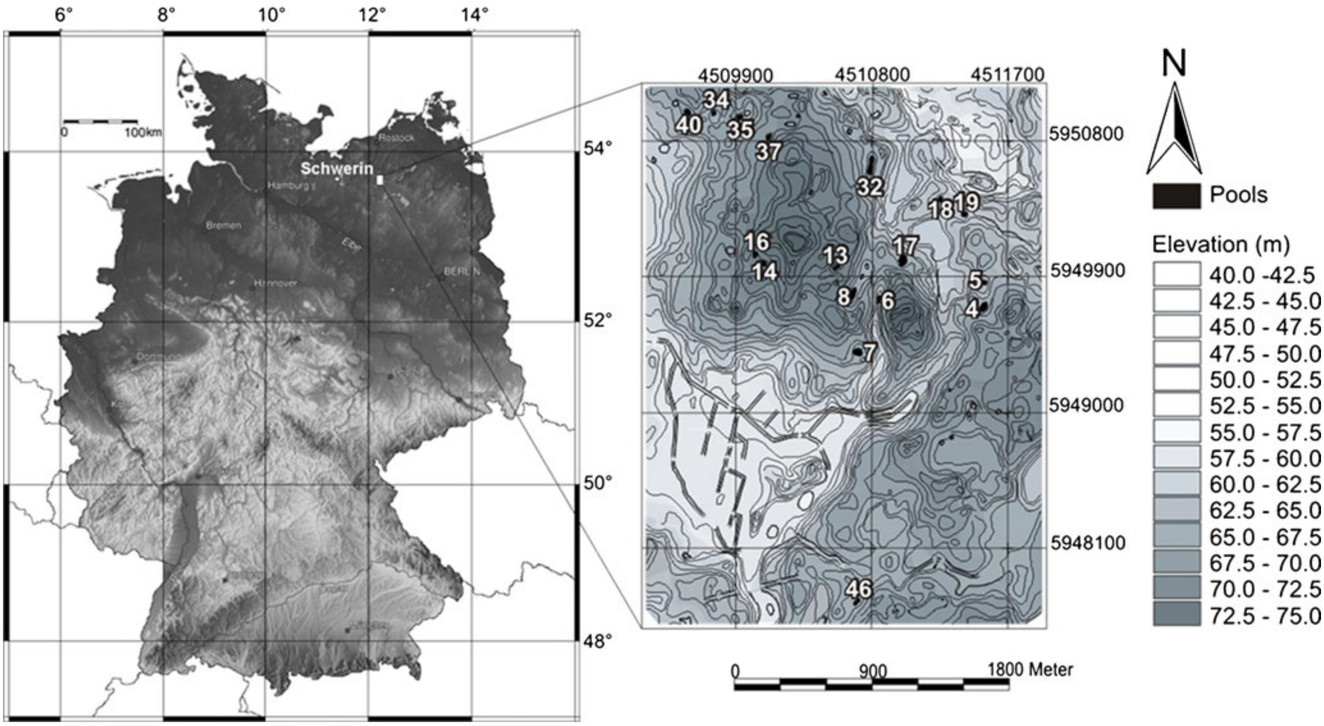

Fig. 1 Map of the study area in North East Germany with distance to the weather station, Schwerin, and all investigated kettle holes, named as pond numbers

distribution function (PIII df). The PIII df has a physical basis as it describes the response of a series of coupled linear reservoirs (known as the Nash-cascade), but it can only mimic the transfer through both the saturated and unsaturated zones and does not give an exact solution. Mathematically, the PIII df (Θ(t)) is defined by:

$$\Theta(t) = A^* \frac{\alpha^n t^n e^{-\alpha t}}{\Gamma(n)} \quad (1)$$

where t is time, A, α, and n are parameters that describe the shape of the IR-function (Von Asmuth and Knotters 2004), and $\Gamma(n)$ is a the gamma function (Abramowitz and Stegun 1964).

The response to potential evaporation is considered to be the same as to precipitation (but negative), except for a reduction parameter that allows for an average reduction of the potential evaporation, calculated according to the FAO 56 guidelines (Allen et al. 1998; Von Asmuth et al. 2008). This evaporation reduction parameter includes different vegetation cover effects and soil dryness factors. The difference between the simulated and observed time series is called the 'residual series.' The residual series is modelled separately with a noise model, which removes autocorrelation (i.e., dependencies between observations) from the data. For a thorough description and clarification of the functioning of the noise or stochastic part of the model, see von Asmuth and Bierkens (2005). Therefore, the model requires only five different parameters: three for the precipitation series (A, α, and n); one for evaporation; and one for the noise model. Models were generated for each kettle hole using the two-year daily water level observation data for calibration. These models were used to simulate water levels of all 17 kettle holes on a daily basis between 1950 and 2004. With the aim of later applying the results to ecological investigations, the following statistics were calculated to describe the water level dynamics in the ponds: the annual spring high water (SHW) level, estimated by the maximum water level between the 16 March and 15 April; the annual mean water (AMW) level, estimated by calculating the mean of the daily water levels between 16 June and 15 July; the annual autumn low water (ALW) level, estimated by the minimum of the daily water levels between the 16 September and 15 October; the annual water level fluctuation (LF), defined by the difference between the maximum and minimum water level of a year; and the winter filling (WF), defined by the differences of autumn low water level and following spring high water level.

Time series of 10-year moving averages of these annual hydrological statistics were calculated. These time series were used to analyze trends in annual hydrological statistics using simple linear regression functions. Finally, correlations were tested between annual hydrological statistics and annual and inter-annual climate statistics, such as PPT and PET.

Results

Measured Water Levels

Compared to records of the last 100 years, PPT and PET during the 2002 and 2003 study period can be classified as climatological extremes. The first year was wet and nearly reached the 95th percentile of precipitation surplus. The second year was very dry and below the 25th percentile of precipitation deficit. In 2002, the wet year, the water level fluctuations between highest and lowest measured water depths varied from 0.08 m to 0.44 m among the kettle holes. The measured maximum water depth ranged up to 2.06 m. In 2003, fluctuations varied from 0.26 m to 1.32 m, three times higher than the values of 2002. It was assumed that maximum water levels measured in spring in 2003 would be influenced by the very wet climatic conditions in 2002. However, measured maximum water level decreased, compared to the maximum in 2002, and ranged between 0.31 m and 1.82 m water depth.

Time Series Models

Parameters describing the performance of the models are displayed in Table 1. Explained variance percentage (EVP), which indicates the success of the calibration, was above 87% for every pond. Estimated values for the local drainage base (dBase), defined by the level of the surrounding ground-water system or in the case of no connectivity to ground water, defined by the low permeable sediment layer underlying the pond, ranged between +1.0 m water depth and −1.6 m. The drainage resistance of precipitation (P1) is defined by the area or zeroth moment of the response function (von Asmuth and Maas 2001). Estimated values varied from 145 days to eight years, indicating that pond characteristics differ considerably. Regarding precipitation, for the fastest reacting pond, 95% of a precipitation event runs off into the pond within 145 days on average. For the kettle hole with the slowest reaction time to precipitation, the time span between a precipitation event and its infiltration into the pond was 16 times as long. The evaporation reduction parameter (P4) scales the evaporation from potential to actual by a static factor. Values for this parameter varied among the models from 0.26 to 0.94.

Simulations

To compare the hydrology of different kettle holes, we used the mean values of the whole simulation period of the previously described annual statistics (Table 2). The mean SHW levels varied between 0.16 m and 1.20 m water depth. The AMW level over the whole simulation period (MW) varied between −0.1 m and +1.0 m water depth among the observed kettle holes. The mean ALW level

Table 1 Calibration statistics and model parameters for all 17 kettle holes

Pond No.	EVP	dBASE (m)	Precipitation		Evaporation	
			Drainage resistance of PPT P1 (days)	Std	PET reduction factor P4	Std
4	95.3	0.90	145	3	0.81	0.01
5	96.5	0.75	261	9	0.79	0.01
6	94.1	0.26	391	39	0.49	0.01
7	94.5	0.33	224	23	0.51	0.01
8	92	−0.05	911	67	0.26	0.01
13	98.7	0.65	281	6	0.94	0.01
14	94.7	0.80	470	10	0.66	0.02
16	99.3	0.62	1116	24	0.57	0.01
17	93.7	0.37	389	42	0.62	0.01
18	96.4	0.43	514	39	0.63	0.01
19	94.9	0.45	464	45	0.63	0.01
32	98.8	−1.61	2858	68	0.38	0.01
34	93.1	−0.20	1082	120	0.68	0.01
35	91.4	−0.97	1041	87	0.32	0.01
37	93.2	−0.75	1089	65	0.38	0.01
40	87.1	0.97	297	11	0.77	0.01
46	96.9	0.71	687	35	0.58	0.01
Min	87.1	−1.61	145		0.940	
Max	99.3	0.969	2858		0.260	

Table 2 Estimated water level statistics for all kettle holes, based on model simulations over a period of 54 years

(m) Pond No.	Mean spring high water level (MSHW)	Mean water level (MW)	Mean autumn low water level (MALW)	Mean annual fluctuation (MLF)
4	1.06	0.87	0.63	0.44
5	0.90	0.70	0.47	0.46
6	0.60	0.48	0.30	0.35
7	0.53	0.44	0.32	0.25
8	1.02	0.96	0.82	0.29
13	0.78	0.51	0.18	0.63
14	1.18	0.87	0.51	0.70
16	1.22	1.03	0.77	0.51
17	0.58	0.47	0.31	0.31
18	0.79	0.54	0.21	0.64
19	0.76	0.55	0.27	0.54
32	1.05	0.77	0.29	0.96
34	0.31	−0.10	−0.61	1.00
35	0.16	0.03	−0.21	0.49
37	0.30	0.14	−0.17	0.63
40	1.20	0.93	0.59	0.65
46	1.23	0.94	0.59	0.69

varied between −0.61 m and +0.82 m water depth. The mean WF ranged between 0.25 m and 1.00 m. Hence, the hydrological dynamics of the kettle holes varied widely.

The 10-year moving average time series investigations showed that SHW levels differ considerably among the years. Differences in SHW of the same kettle hole ranged from 0.26 m to 2.50 m over the simulated period (Lehsten 2009; data not shown). Trends in SHW, however, are not obvious (Fig. 2a). In contrast to the SHW levels, the ALW levels, WF, as well as LF show linear trends (Table 3). However, the r^2 and P-values are weak or not significant for ponds 8, 32, 35, and 37. While ALW decreased with time (Fig. 2b), LF and WF increased (Figs. 2c and 2d).

Relationships between the climatic driving forces and hydrological annual water level statistics were examined. Cumulative evaporation over the growing season (1 April to 30 September) correlated well with ALW level in the following year. Additionally, annual precipitation calculated from 1 April correlated well with SHW level of the following year. One would assume that winter precipitation (1 October to 31 March) correlated with the SHW. However, this relationship was not found in the simulation results. The sum of the winter precipitation of two successive years, however, correlated well with WF of the second year. Linear correlations between winter precipitation and WF were not as strong as correlations between annual precipitation and SHW or between cumulative evaporation over the growing season and ALW. All correlation factors and p-values are shown in Table 4. Simulation results for pond 37 did not exhibit climatic dependencies.

The climate time series used for simulation were examined over 57 years (beginning in 1947). The 10-year mean of daily maximum temperature was calculated and plotted with a weekly time step (Fig. 3a). Between 1947 and 2004 the 10-year mean of daily maximum temperature increased by nearly 1°C (linear trend: $r=0.80$, $p<0.001$). The 10-year mean of annual precipitation was plotted over the same period (Fig. 3b), but no obvious trend in precipitation was found ($r=-0.40$, $p=0.06$). The 10-year mean of annual precipitation varied between 570 mm and 680 mm per year over the time period. In contrast to annual precipitation, the winter precipitation (between 1 October and 31 March) increased by approximately 50 mm (linear trend: $r=0.91$, $p<0.001$) over this period (Fig. 4).

Discussion

To protect the wide variety and number of kettle holes it is important to understand how they respond to changes in climate (Ferone and Devito 2004). In this study the time series model PIRFICT was used to model the water level dynamics of kettle holes with respect to climate but without detailed knowledge of hydrological properties. Time series analysis technique can be used for a wide range of hydrological systems (Okkonen and Klove 2010). Pyke (2004) developed and applied a time series model (PHYDO: PoolHYDrOlogy) for vernal pools in 2004. Inputs for this model are climatic time series as well as pool environmental characteristics. Although this model

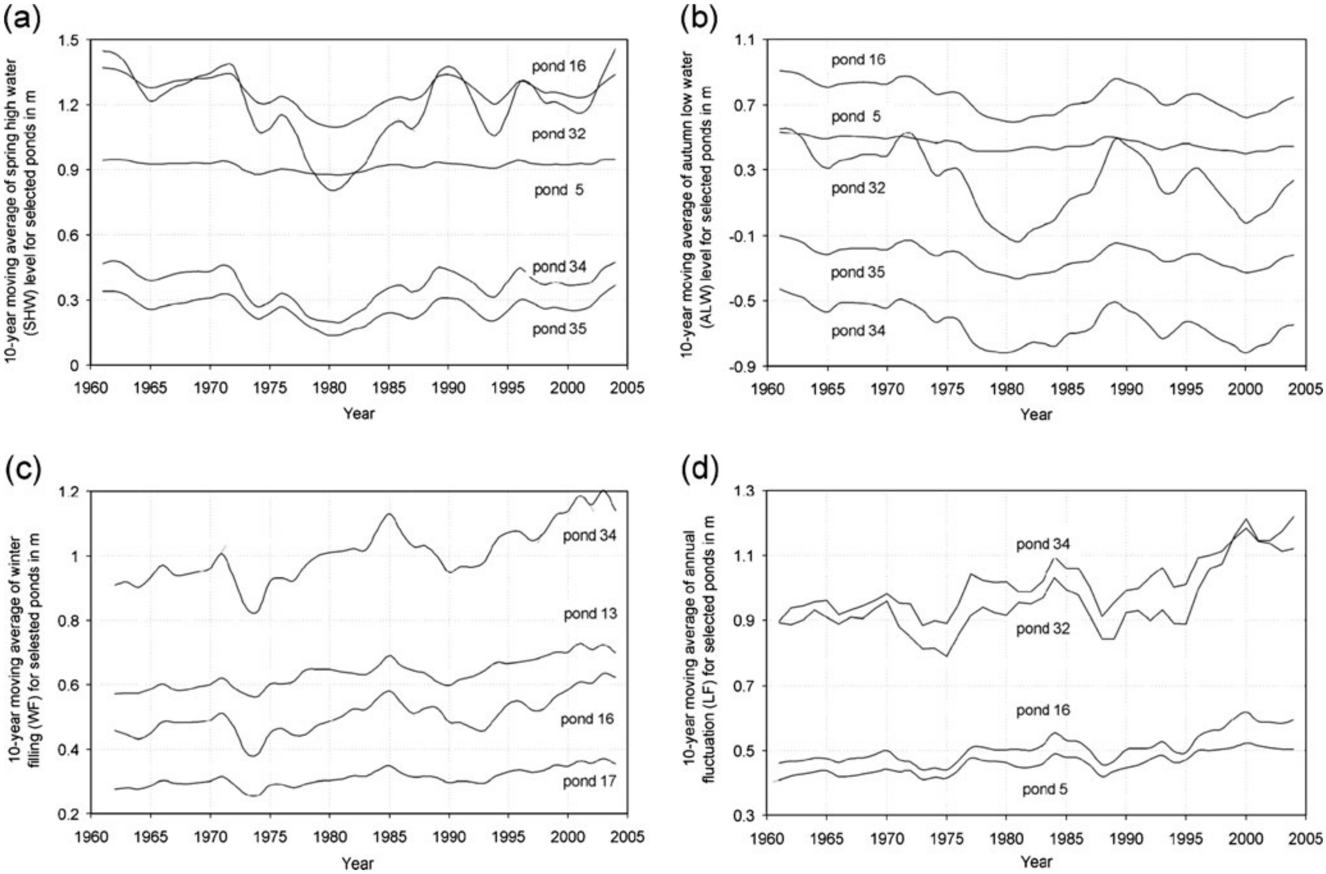

Fig. 2 Ten-year moving average for selected ponds of (**a**) spring high water (SHW) level, (**b**) autumn low water (ALW) level, (**c**) annual fluctuation (LF), (**d**) winter filling (WF)

Table 3 Results of linear-trend analysis of the 10-year moving average of annual water level fluctuations, winter filling, and autumn low water levels of the 17 kettle holes between 1950 and 2004 (window of 10 years). P-values marked with * are<0.01, marked with ** are<0.001

Pond No.	LF r^2	LF p	Increase of LF (m)	WF r^2	WF p	Increase of WF (m)	ALW r^2	ALW p	Decrease of ALW (m)
4	0.73	**	0.1	0.74	**	0.08	0.70	**	0.1
5	0.7	**	0.11	0.72	**	0.09	0.51	**	0.11
6	0.55	**	0.08	0.52	**	0.07	0.38	**	0.09
7	0.53	**	0.05	0.53	**	0.05	0.42	**	0.06
8	0.32	**	0.07	0.30	**	0.07	0.16	*	0.09
13	0.74	**	0.16	0.75	**	0.12	0.57	**	0.15
14	0.66	**	0.19	0.67	**	0.16	0.45	**	0.17
16	0.62	**	0.15	0.54	**	0.13	0.31	**	0.21
17	0.66	**	0.08	0.62	**	0.07	0.39	**	0.09
18	0.61	**	0.15	0.61	**	0.12	0.45	**	0.16
19	0.62	**	0.13	0.62	**	0.11	0.43	**	0.14
32	0.45	**	0.30	0.03	0.31	−0.09	0.22	**	0.38
34	0.65	**	0.26	0.63	**	0.22	0.37	**	0.29
35	0.43	**	0.11	0.38	**	0.1	0.23	**	0.14
37	0.18	*	−0.11	0.26	**	0.28	0.11	0.027	−0.09
40	0.7	**	0.16	0.72	**	0.12	0.60	**	0.16
46	0.57	**	0.18	0.55	**	0.15	0.32	**	0.17

Table 4 Correlation factors (r) and p-values of correlation between ALW level and summer evaporation, between SHW level and annual precipitation rate, and between WF and winter precipitation. P values<0.001 are marked with **

Correlation factors	ALW to summer evaporation		SHW to annual precipitation		WF to winter precipitation of two successive years	
time delay in years	1		1		0	
Pond No.	r	p	r	p	r	p
4	−0.83	**	0.72	**	0.31	0.006
5	−0.78	**	0.88	**	0.48	**
6	−0.62	**	0.85	**	0.55	**
7	−0.68	**	0.83	**	0.50	**
8	−0.31	0.023	0.79	**	0.63	**
13	−0.82	**	0.87	**	0.44	**
14	−0.75	**	0.87	**	0.50	**
16	−0.46	**	0.86	**	0.71	**
17	−0.60	**	0.88	**	0.63	**
18	−0.71	**	0.87	**	0.52	**
19	−0.71	**	0.88	**	0.52	**
32	−0.36	0.008	0.83	**	0.67	**
34	−0.64	**	0.91	**	0.61	**
35	−0.41	0.002	0.83	**	0.61	**
37	0.05	0.718	0.10	0.429	−0.23	0.188
40	−0.81	**	0.82	**	0.41	**
46	−0.64	**	0.89	**	0.59	**

simulates pool hydrology effectively, its limitations are seen in regard to the input parameters it requires and in its restricted application to vernal pools without groundwater connectivity. The PIRFICT model requires even fewer input parameters than PHYDO, only precipitation (PPT) and potential evaporation (PET) time series and it can be applied to all kinds of ponds.

However, assumptions such as the stationary and linear nature of the system should be addressed. This means that the responses of the system to PPT and PET are assumed to be more or less constant. Because of this, the delayed contribution of snow precipitation, as well as snow melt run off, are considered in the model as continuous flow through the soil. Hence, spring high water levels might be underestimated (Poiani et al. 1995) while winter water levels might be overestimated.

Intermittent water loss or gain due to superficial runoff or leakage may cause non-linear responses of the model output parameter ‘water depth’ to the model input parameters (although not observed during our study). In such cases, as described by Kalettka and Rudat (2006), a threshold non-linear time series model should be applied

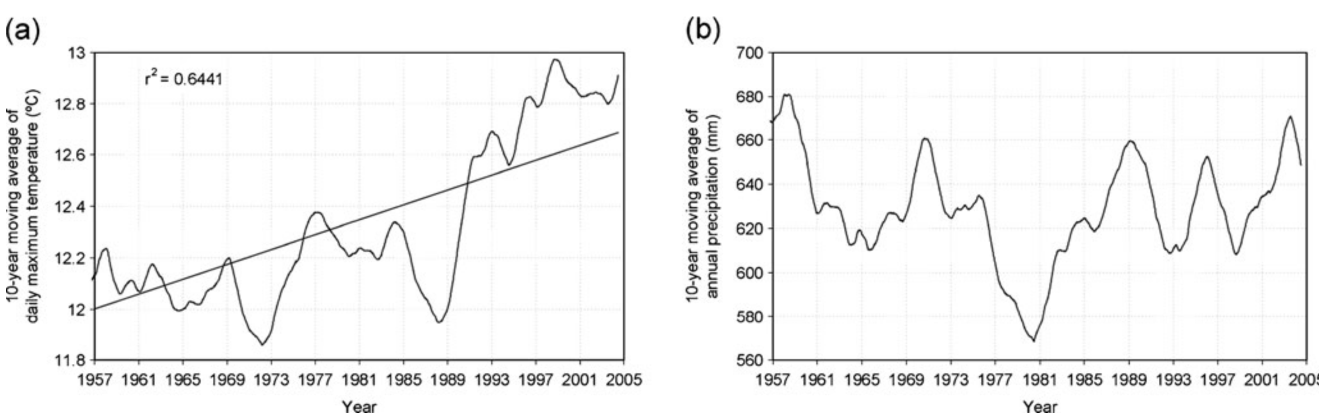

Fig. 3 Ten-year moving average of (**a**) daily maximum temperature (°C) and (**b**) annual precipitation (mm); time step one week

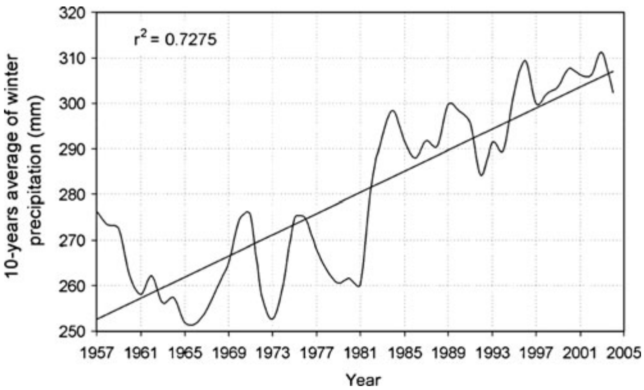

Fig. 4 Ten-year average of winter precipitations (mm), time step one year

to the data (e.g., Von Asmuth and Knotters, unpublished). Response to evaporation is also affected by the linearity assumption. The PAN evaporation method, based on the FAO 56 guidelines (Allen et al. 1998), was applied and calibrated with parameter P4. For the sake of simplicity, P4 was set constant over time for each model because it was parameterized by observations taken mainly over the growing season and thus might be overestimated for the winter.

The two extreme years in weather conditions used for our time series analysis exhibit a full range of climate variability. However, for cross validation and because of the effects of extreme weather conditions, we suggest that the measurement plan for future studies on pond water level dynamics be carried out over a period of at least three years.

Moorhead (2003), Johnson et al. (2004), and Dempster et al. (2006) all indicated that water tables of small water bodies respond to extreme weather conditions (either dry or wet). These responses may exhibit a time delay in relation to periods with high precipitation or evaporation rates (Woo and Rowsell 1993; Schmidt 1996). The time lags identified by Schmidt (1996) and Woo and Roswell (1993) were two years and at least 1 year, respectively. Our study also had a time delay of one year in response to summer evaporation and winter precipitation. Delay might be affected by the perched/ground-water aquifers surrounding ponds, which can act as buffers. Surface runoff raises water tables in kettle holes, causing lateral infiltration into the soil (Hayashi et al. 1998), feeding the lower surrounding perched/ground-water tables (Pierce 1993). This process reduces the effect of water runoff. Evaporation, on the other hand, decreases pond water tables, resulting in a lower hydraulic pressure compared to perched/ground water. Soil water can percolate into kettle holes and feed them (Pierce 1993), which reduces the response of the water table to evaporation. Several researchers have suggested and verified such opposing flow direction systems (Woo and Rowsell 1993; Winter and Rosenberry 1995; Ferone and Devito 2004; Sun et al. 2006; Pyzoha et al. 2008).

In this study, the hydrology of kettle holes was analyzed only with respect to climate. Neither oasis effects (Oke 1978) nor human impacts (such as land amelioration, changes in farming practice or land management) were examined. Fast and tall growing wetland plant species with high transpiration rates are fostered by the oasis effect (Lenssen et al. 1999; Pauliukonis and Schneider 2001) and by high sediment deposition rates (Pokorny and Hauser 2002), which further increases summer evaporation. Land amelioration, such as drainage systems, can reduce the water levels of kettle holes. All these impacts could amplify the trend we simulated of decreasing low water levels. They may also result in a higher risk from longer dry seasons (Poiani et al. 1995) and change habitat quality conditions (Keddy et al. 2000), which can alter pond biology (Vivian-Smith 1997; Middleton 1999; Keddy 2002; Raulings et al. 2010). Changes in species composition may already be occurring as *Salix* species and *Solanum dulcamara* have both increased in the study kettle holes over the last 30 years (personal comment Neubauer 2002).

Predicted climate changes in the 21st century, with a projected rising global mean temperature of 1.8 to 4.0°C (IPCC 2007), may profoundly affect pond hydrology and vegetation structure. We suspect that kettle-hole hydrology will change if the current trend of the changing climate continues, and we provide a tool for landscape management and environmental protection organizations to use for estimating the risks of hydrological changes for a wide range of ponds.

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