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An integrated approach to hydropower impact assessment. I. Environmental features of some Norwegian hydro-electric lakes

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Abstract

This paper launches concepts instrumental to environmental impact assessment (EIA) studies on hydropower schemes and lake regulations. Norwegian hydro-electric lakes (hydrolakes) and their environmental features are described, and evaluated against non-manipulated waters. A tentative classification of hydrolakes vs. natural waters is proposed. The need for a multiple approach to habitat classification is emphasized. Recommendations for future biological impact assessment approaches are suggested.

Hydrolakes differ broadly from natural lakes by combining physical features not ordinarily co-occurring in non-manipulated water bodies. Storage type hydrolakes (reservoirs) feature winter draw-downs and enhancement of yearly level fluctuations; whereas other types of hydro-electric lakes have elevated water levels throughout winter. Hydrochemistry and optics of the studied hydrolakes exhibited no clear differences to non-impacted Norwegian inland waters. All lakes had signs of sublacustrine erosional activity related to internal waves and thermocline movements.

Introduction

The prime objective of this study is to characterize the ecological features of a regulated lake (hydrolake) which is operated for production of hydro-electric power (HEP). The applied vehicle for such analysis should transcend the traditional barriers between the fields of hydrology, physical limnology and hydrodynamics, statistics, engineering, and biology (Kuusisto, 1984). The aim is to provide a reference framework upon which a penetrating assessment of regulation impacts to aquatic biota can be made. I deliberately concentrated on submerged macrophytes because these species by their ecophysiology directly relate to the impacted aquatic ecosystem (Hutchinson, 1975). The suggested approaches to environmental impact assessment (EIA) should be applicable to a wider class of lake biota, however.

Some sixty percent of Norway's hydro-electric power (HEP) potential has been developed so far (Statistisk Sentralbyrå 1983: 12). The Norwegian HEP production system is based upon numerous reservoirs (believed to number more than 900, but no official statistics are available) which are augmented by comprehensive catchment transfers, river abstractions, and river diversions. Norwegian HEP plants are largely operated within a national network in order to reallocate powerline current load and power demand, and enhance efficient use of retained water.

The national HEP production amounts to ≈ 100 TWh yr^{-1} (1985), making Norway a world leader in per capita HEP consumption (some 25 MWh yr^{-1}).

The Norwegian hydro-electric reservoirs mainly are impounded natural lakes with an artificially extended water-level schedule. Control structures are also developed on many rivers within ongoing hydropower schemes. The majority of larger lakes in Norway are operated for HEP use. The regulation height of the reservoirs is commonly less than 10 m, but the maximum legislated water-level fluctuation of a Norwegian hydro-electric lake is no less than 140 m. An estimated 23% are regulated less than 5 m and some 22% are regulated 5–9.9 m (Statistisk Sentralbyrå 1983: 27). The percentage of strongly regulated hydrolakes, with regulation heights exceeding 20–30 m, now is rapidly increasing.

Norwegian environmental protection agencies, central authorities, and nature conservancy movements, all express a need for better criteria to evaluate proposed hydropower schemes and their putative impacts to existing lakes and lake biota. The present study aims to provide a means to this end by addressing the following specific objectives: (i) to characterize hydrological and physical features of hydrolakes under biological as well as conceptual perspectives, and elaborate their relationship to natural water bodies; (ii) to determine how aquatic vegetation relates to the physical impact of lake regulation or extended water-level schedule, and in particular, to predict whether critical thresholds for regulation extent can be developed such that ecosystem response meets some preset criteria; (iii) to determine if the regulated lake is resilient to impact on an integrated community level, i.e., are community measures apart from species composition, such as spatial structure and productivity, influenced less than species diversity; (iv) to predict how adverse regulation impacts can be abated by selection of alternative life strategies.

Objective (i) is the scope of the present paper, which is a preamble to two planned companion papers (Rørslett, in prep.). These deal with the other issues presented above, and attempt a synthesis of this approach to environmental impact assessment (EIA).

Throughout this series of papers, emphasis is put on all aspects of vertical distributions for environmental as well as for macrophytic data. Furthermore, my analysis focuses on broad features of the responses exhibited by the included lakes, and so many details shall regrettably be left out. The underlying rationale for this approach is now briefly elaborated.

The aquatic and terrestrial habitats are fundamentally different (Hutchinson, 1975). Across a vertical gradient, the aquatic-terrestrial interface can be defined at the median water level (Rørslett, 1984). Hence the aquatic and terrestrial habitats are located below and above that reference level, respectively.

The major environmental gradient in any lake relates to depth (Cf., Hutchinson, 1975; Rørslett, 1984). Plants are distributed across this vertical gradient according to niche preferences. Neglecting within-lake gradients, the *spatial niche* projects on to segments of the vertical gradient (Keddy, 1982, 1983; Rørslett, 1984). Thus, the niche description simplifies to the spatial coordinates of the vertical dimension, and the associated point-time probability distribution of environmental factors (Rørslett, 1984, 1987b). In regulated lakes, it is necessary to distinguish between depth and relative elevation, i.e. spatial position in the vertical gradient. Depth is equivalent to the height of water overlaying the plants at any time, thus the instantaneous value may be nil and as demonstrated by Rørslett (1984), the niche description of any submerged macrophyte has to take the probabilistic nature of water-level fluctuations into account.

Material and methods

Studied lakes

During the years 1976–1986, I collected a substantial data base on the vegetation, hydrology, morphometry, and hydrochemistry, of several Norwegian lakes. Data from 17 lakes, spanning a wide range of areas, altitudes, and nominal extent of regulation, are presented here. These lakes are listed in Table 1 and their geographical locations are indicated on Fig. 1. Some lakes with a naturally extensive range of water-level fluctuations also are included.

I relied mainly on photographic sampling for macrophytes and sediment data. Details are reported elsewhere (Rørslett *et al.*, 1978; Rørslett, 1987c). The data base comprises mainly clear-water, oligotrophic lakes. One lake, viz. Steinsfjord, is in many respects strongly deviating from the other lakes. This lake is meso- to eutrophic, and currently is heavily infested with *Elodea canadensis* Michx. (Rørslett *et al.*, 1986).

Coordinate domains

Because the water levels fluctuate throughout time, it is crucial to discern the depth D[z] of a point in the vertical gradient from the vertical position z, or relative elevation (height), of that point. Depth D[z] in its time-averaged sense is equivalent to the mean or expected height of the water column overlaying the point in the vertical gradient (Rørslett, 1984).

From the definitions of Rørslett (1984), two contrasting coordinate systems, or spatial domains, can

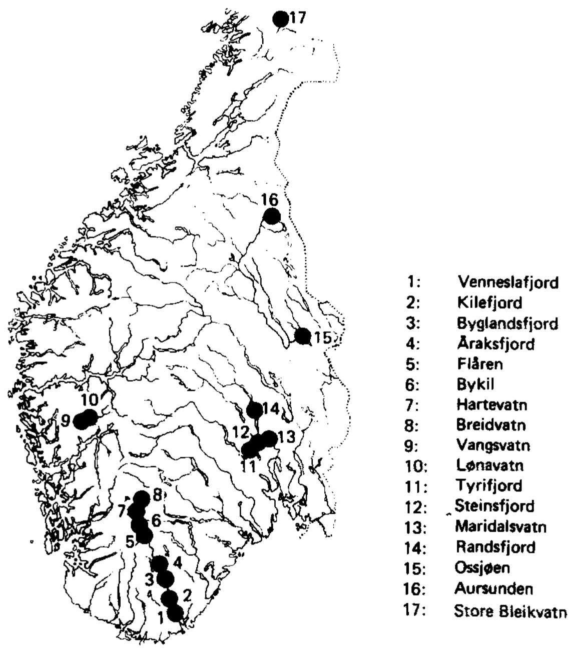

Fig. 1. Geographical locations of the studied lakes in Norway. The 'Setesdal' lakes comprise nos. 1–8.

Table 1. Investigated lakes. Basic morphometric and hydrological data, explicit use for hydro-electric production (HEP) and initial classification indicated.

Lake	HEP use	Type†	Altitude (m)	Area (km^2)	Water-level ranges (m)			
					Nominal*	Annual		Total**
						mean	max.	
Venneslafjord	Yes	ST	38	1.7	NA	1.3	2.8	3.1
Vangsvatn	No	NL	46	8.0	NA	4.5	6.3	6.6
Tyrifjord	±	NL	63	121.9	1.0	2.0	2.9	3.5
Steinsfjord	±	NL	63	13.9	1.0	2.0	2.9	3.5
Lønavatn	No	NL	77	3.0	NA	≈1.5		≥2.0
Randsfjord	Yes	SR	134	136.9	3.0	2.9	3.9	4.2
Maridalsvatn	No	NL	148	3.9	2.0	1.1	1.3	1.6
Kilefjord	Yes	ST	167	5.5	1.5	2.0	2.9	3.2
Byglandsfjord	Yes	SR	202	30.7	5.0	3.6	4.9	5.9
Åraksfjord	Yes	SR	203	11.2	5.0	3.5	4.9	5.0
Flåren	No	NL	274	1.4	NA	≈1.5		≈2.5
Store Bleikvatn	Yes	SR	400	11.4	21.5	11.3	14.4	15.0
Ossjø	Yes	SR	435	45.2	6.6	5.9	6.6	6.6
Bykil	±	NL	500	1.0	2.0	≈1.0		≥1.5
Aursunden	Yes	SR	689	44.0	5.9	5.5	6.1	6.1
Hartevatn	Yes	SR	757	6.0	7.0	6.4	7.3	7.8
Breidvatn	Yes	SR	897	3.1	2.5	3.0	3.5	3.5

† Group designations are: SR = storage reservoirs, ST = short-time regulated lakes, NL = (semi-)natural lakes. See text for additional details.

* Nominal regulation height as licensed by Norwegian authorities. NA = not applicable (unregulated or no fixed range legislated).

** Total within-lake range for all years 1945–1982.

be derived (Rørslett, 1987a): The fixed coordinate, or Eulerian, system and the moving coordinate, or Lagrangian, system (Fig. 2). Rørslett (1984, 1987a) demonstrated that the Eulerian system was related to the Lagrangian system by a convolution. The convolution kernel $p_v[\cdot]$ enables the mapping of Lagrangian-coordinate functions (v-domain) into the corresponding Eulerian (z-domain) functions (Rørslett, 1987a),

$$E\,H[z] = \int_{-\infty}^{\infty} h[u-z]\,p_v[u]\,du = \int_{-\infty}^{\infty} h[v]\,p_v[v+z]\,dv \qquad [1]$$

where E is the expectation operator
H[] is an Eulerian domain function with spatial coordinate z
h[] is the Lagrangian domain function with coordinate $v = u - z$
p is the convolution kernel
u is a Lagrangian coordinate $u = u[z]$ at $z = 0$

Formally, the kernel represents the probability density function (pdf) of the Lagrangian coordinate, v. By orienting the Eulerian coordinate system as shown on Fig. 2, this kernel also equals the pdf of water levels related to the median water level ($z = 0$) (Cf., Rørslett, 1984).

Environmental data

Hydrochemical investigations were carried out by the Norwegian Institute for Water Research (NIVA, Oslo) from the 1970's onwards. Water analysis followed Norwegian Standards (automatic and manual methods). Photosynthetic available radiation (PAR, 400–700 nm) was measured with a Li-Cor LI-185

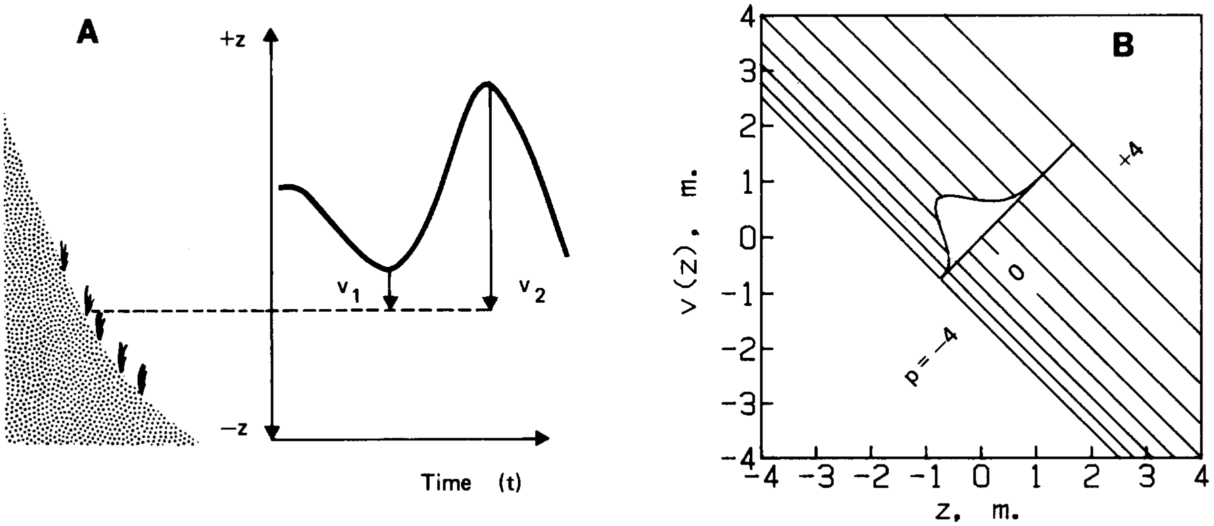

Fig. 2. Spatial domains for description of a macrophyte's vertical extension, when the water levels fluctuate throughout time. Two contrasting approaches are possible; the fixed-coordinate and the moving-coordinate approach. A: Fixed-coordinate (Eulerian) z-domain vs. moving-coordinate (Lagrangian) v-domain. For Eulerian coordinates, the datum ($z = 0$) is the median water level, such that z negative is located below and z positive is located above that reference level. Lagrangian coordinates have the instantaneous lake level as their datum and are oriented positively downwards (thus they conform to the common usage of the 'depth' concept). When lake levels fluctuate, depth to a fixed spatial postition (e.g. a bed of macrophytes) alters with time. On the figure, this is shown by the depths v_1 and v_2, respectively. B: Lagrangian (v) coordinates can be transformed into Eulerian coordinates (z) through the probability density function of the water levels, $p_v[z]$. Each z-value is then associated with a *stochastic* distribution of v-coordinates, $v = v[z]$. This distribution is identical to that of $p_v[v + z]$. Refer to eqn. (1) for details of this coordinate transformation.

Indicated are a Lognormal density LN (μ_y, σ_y^2) of water levels and the v-isolines of this distribution, given by: exp (μ_y) [exp ($p\sigma_y$)-1]; with p ranging from -4 to $+4$. For an LN distribution, the water-level median is at $p = 0$. Hence according to eqn. (1) the expected value of the Lagrangian coordinate at $z = 0$ is, E v[0] = exp ($\sigma_y^2/2$), which always must be >0. This illustrates the basic fact that z- and v-coordinates cannot be freely interchanged unless a stochastic mapping (eqn. (1)) is applied. Refer to Rørslett (1984, 1987a) for mathematical details.

Quantum meter and sensor LI-192SB (Lambda Instruments, Inc.) intermittently during the summer months. Vertical attenuation coefficients k_{PAR} (ln-units m^{-1}) were estimated by a non-linear least squares approach (Rørslett, 1987a), and are averaged over the water column sampled.

Water-level data were obtained from official water gauges monitored by the Norwegian Water Resources and Electricity Board (NVE, Oslo). Daily measurements for the years 1945 to 1982-85 were available. Computed statistics included annual means, maximal annual ranges, total range, and cumulative probability distribution using 0.01 m or 0.05 m vertical resolution. The water-level medians could then be computed directly from the probability distributions. Ice-scour impact, IS[z], in the littoral zone was estimated by convolution of an influence 'box' function with the probability density function of water levels in the ice-covered period (Rørslett, 1984).

Spectral analysis

Basically, spectral analysis provides a breakdown of total variance into its frequency components. Mathematically, this is achieved by the Fourier integral transformation of a zero-mean time series x' [t] defined for $|t| \leq T/2$, such that;

$$XX'[f] = 1/T\left|\int_{-T/2}^{T/2} x'[t]\, h[t] \exp(-i2\pi ft)\, dt\right|^2 \qquad [2]$$

where: h[t] is a window (tapering) function
i is the imaginary unit number ($i^2 = -1$)

The Fourier transform represents the original data as a (finite) sum of cosines and sines, by assuming that x'[t] h[t] is zero outside the interval (−T/2, T/2). From Eqn. (2), XX' [f] is a real-valued, non-negative and even function, called the spectral density of x'[t]. Because the mean of x'[t] is zero, XX'[f]df is the variance component in the frequency interval (f, f + df). Only positive frequencies are considered since XX' is an even function and hence should be doubled to obtain the final variance estimates.

Spectral analysis of the water-level time series was performed with a Fast Fourier Transform (FFT) algorithm, originating from Welch (1967). As h[t] function, I applied the Parzen window (Jenkins & Watts, 1968). Frequency resolution was adjusted by flexible oversampling, and the annual component ($f = 1\ yr^{-1}$) nominated as the fundamental frequency (f_0). Higher integer-valued frequencies (f = 2, 3, ...) are then designated harmonics (2nd, 3rd, ...) of the fundamental.

Miscellaneous measures derived from the spectrum

Additional measures can easily be derived from the spectrum; however, they should be interpreted as descriptive rather than physical quantities. The variance σ^2 of a cosine curve relates to the amplitude A (≥ 0) by,

$$\sigma^2 = A^2/2 \text{ or } 2A = \sigma\sqrt{8} \text{ (range } -A \text{ to } +A) \qquad [3]$$

When the symmetry of XX' is taken into account, the weighted average range of the time series, $2\bar{A}_\infty$ is given by,

$$2\bar{A}_\infty = 4\sqrt{\left(\int_0^\infty XX'[f]\, df\right)} \qquad [4]$$

By adjusting the integration limits accordingly, similar expressions are obtained for individual frequency bands, $2\bar{A}[f]$. These single-band estimates are computed for a frequency band of width Δf, centered on f. From these single-band estimates, multiple-band estimates can be developed (usually from 0 to f, hence denoted $2\bar{A}_f$).

The average time period, $\bar{T}_p$, can be found from,

$$\bar{T}_p = \left(\left(\int_0^\infty f\, XX'[f]\, df\right) / \left(\int_0^\infty XX'[f]\, df\right)\right)^{-1} \qquad [5]$$

and is a measure of spectral wavelengths (actually, the inverse of the weighted average frequency which itself is a measure of spectral concentration). The units of $\bar{T}_p$ accordingly are $(f_0)^{-1}$.

Results

Initial classification of the lakes

Hutchinson (1957) classified man-made lakes and reservoirs into 'artificial lakes' (type 73); thus all types of hydro-electric lakes are included. Such a broad classification scheme yields groups of little practical value. Here, the lakes provisionally are divided into groups according to their origin and HEP scheme under which the lake is operated. These groups are designated 'storage reservoirs', 'short-time regulated' and 'semi-natural' lakes, respectively (Table 1).

The hydro-electric production use of the studied lakes is indicated in Table 1. Ten out of 17 lakes are regularily operated for HEP. Additionally, three lakes (Bykil, Tyrifjord, and Steinsfjord) are influenced by HEP use within their water-course.

Distribution of water levels

Unregulated Norwegian lakes generally lack water-gauges, so only data from one of those lakes, viz. Vangsvatn, were available. For all lakes with gauge data, the mean annual water-level fluctuation ranged from 1.1 to 11.3 m (Table 1). The entire range of water levels within a regulated lake generally exceeded that officially legislated. This phenomenon is mainly caused by the spillway construction.

The water-level schedules clearly differed between these lakes. Three schedules could be discerned. Broadly defined, the cdf shapes were concave, S-shaped, or convex (Fig. 3), corresponding to a right-skewed, symmetric, or left-skewed probability density, respectively (cf. Figs. 4–5).

Figure 3 shows the cumulative distribution of water levels $\{W_* = w[t] - \tilde{W}\}$, adjusted as deviations from the median level ($\tilde{W}$). The density of this distribution is equivalent to that of the Lagrangian coordinate $v = v[z]$ for $z = 0$, i.e. $p_v[z]$ (Rørslett, 1984, 1987a). Numerically, adjusted water levels (W_*) and vertical Eulerian coordinates (z-domain) coincide. Strictly speaking they involve different concepts, however. The distinction should be addressed in certain circumstances. In order to compare the lakes,

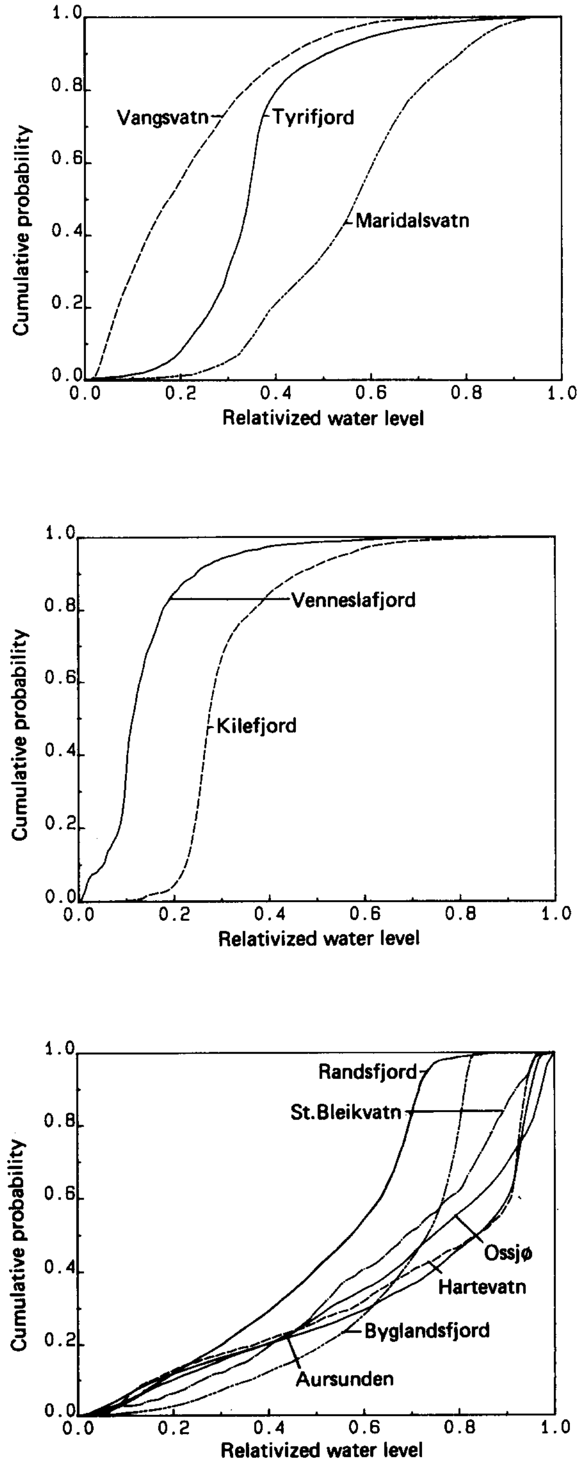

Fig. 3. Cumulative distribution function (cdf) of water levels for representative lakes, plotted on a relativized scale (Cf. text). A: Semi-natural lakes, B: Short-time regulated lakes, C: Storage reservoirs.

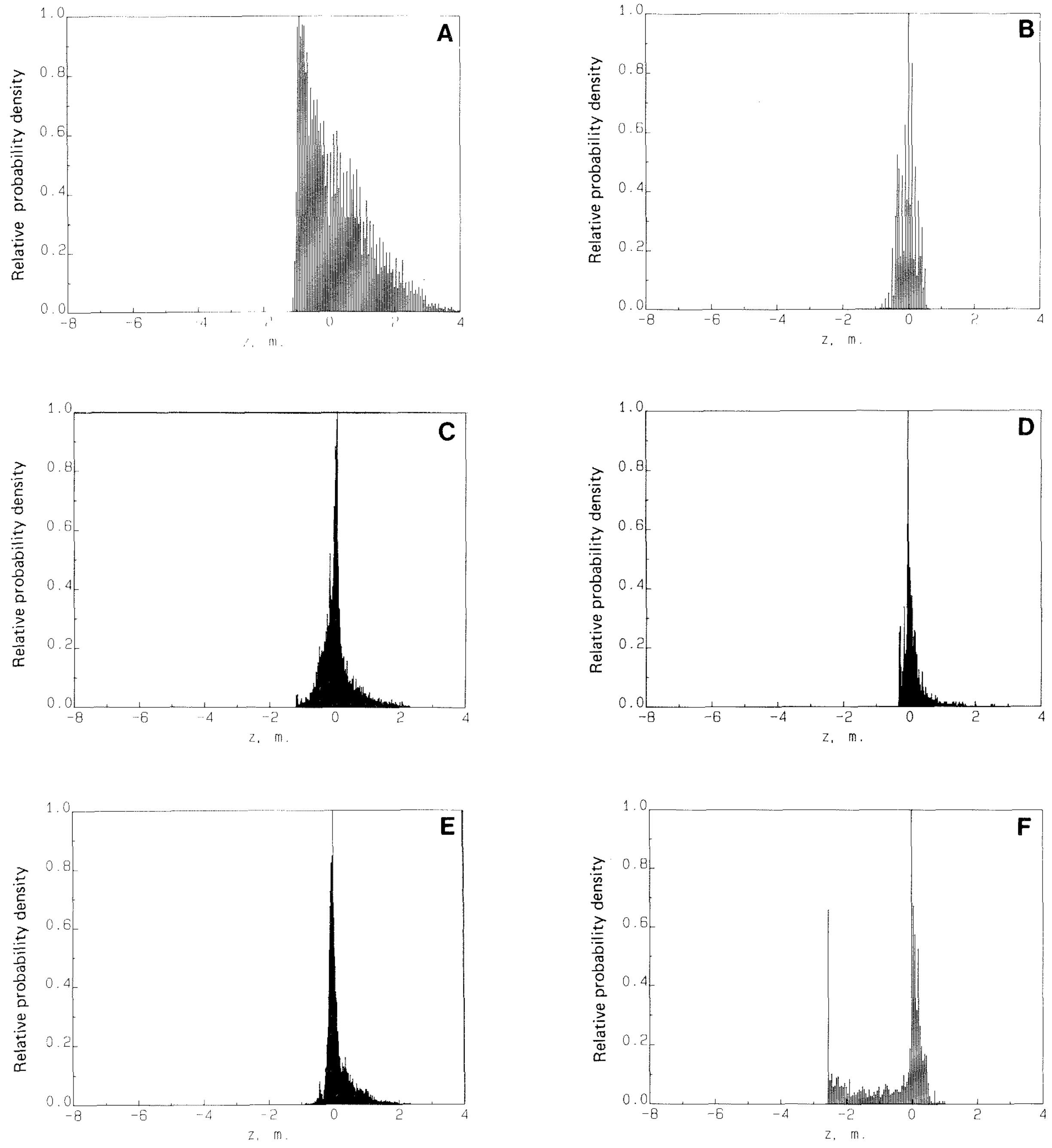

Fig. 4. **Probability density (pdf) of water levels for representative lakes, plotted on the corresponding z-scale (cf. text). Datum of z-scale is located at the median water level for each lake, such that z positive is above and z negative is below the reference level. A: Vangsvatn, B: Maridalsvatn, C: Tyrifjord, D: Venneslafjord, E: Kilefjord, F: Breidvatn.**

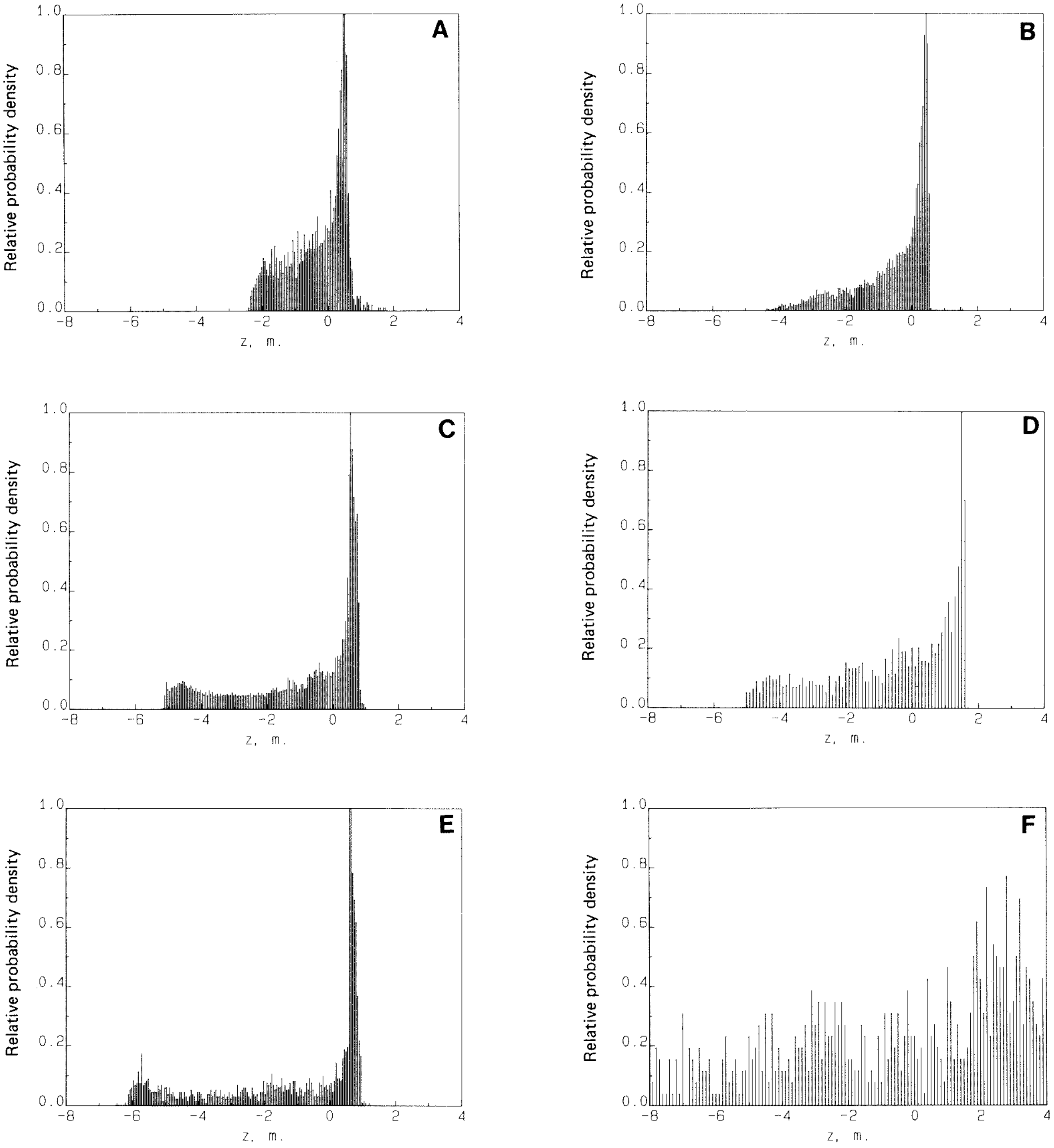

Fig. 5. **Probability density (pdf) of water levels for representative lakes, plotted on the corresponding z-scale (cf. Fig. 4). A: Randsfjord, B: Byglandsfjord, C: Aursunden, D: Ossjø, E: Hartevatn, F: Store Bléikvatn.**

the cdf's $P_v[\cdot]$ are presented on a relative scale, i.e., they are scaled with abscissa $z' = (Z-Z_{min})/(Z_{max} - Z_{min})$. This enables shape comparisons to be made.

The 'semi-natural' lakes (Figs. 3a, 4) are least impacted by water-level management. The water levels within this lake group exhibited fluctuation ranges from 1.1 m up to more than 6 m for Vangsvatn; annual ranges less than 3 m perhaps were most common. Spring run-off from snow-melt of high-and medium-altitude watersheds, often in conjunction with autumn floods, are major causes of extended alterations of lake levels. These lakes featured either right-skewed (Vangsvatn) or fairly symmetric (Maridalsvatn, Tyrifjord, Steinsfjord) pdf's. Lønavatn, Bykil, and Flåren would likely belong to this group of lakes also. Evidently, unregulated lakes possessing outlet sills would show right-skewed water-level pdf's (Vangsvatn, and probably including also Lønavatn and Flåren).

The 'short-time regulated' lake group (Figs. 3b, 4) comprised Kilefjord and Venneslafjord only. Their water-level pdf's closely related to the right-skewed ones of the 'semi-natural' lakes.

The 'storage reservoir' group (Figs. 3c, 4–5) encompassed Breidvatn, Hartevatn, Byglandsfjord, Åraksfjord, Randsfjord, Ossjø, Aursunden, and Store Bleikvatn. All these lakes had strongly convex cdf's reflecting a pronounced left-skewed distribution of water levels. The preferred operation shedule would be to keep the pool levels as close to the spillway stage as possible during the summer, which according to Fig. 5 largely is accomplished.

Water-level fluctuations: frequency domain analysis

Variance (auto-power) spectra were computed for all lakes having sufficient hydrological data over 20 or more years. These data had a folding (Nyquist) frequency, $f_N = 182.5\ yr^{-1}$, so some aliasing by unresolved higher frequencies would be expected to occur. However, the inertia of lacustrine systems should provide an effective low-pass filter attenuating very high frequency components. Thus, pilot spectra run up to f_N indicated that frequencies above $10-15\ yr^{-1}$ contributed negligibly to the total variance. Furthermore, distinct low-frequency peaks occurred in the spectra. The final spectral analysis, run at a frequency resolution $\Delta f = 0.2\ yr^{-1}$, applied a bandwidth of $f_{max} = 25.6\ yr^{-1}$, or about twice the frequency of the highest significant peak.

Most lake spectra had prominent spectral peaks at the annual frequency ($f = 1\ yr^{-1}$) and its first few harmonics (Figs. 6–7). The storage reservoir group in particular exhibited very strong annual peaks. Kilefjord and Venneslafjord, both operated on short-time demand schedules, had dominant semiannual peaks ($f = 2\ yr^{-1}$) and significant high-frequency variances. Being a potable water supply to the city of Oslo, Maridalsvatn showed an irregular spectrum with prominent low-frequency variance and no discernable annual cycles (Fig. 6). The water-level range measure, $2\tilde{A}[\cdot]$, exhibited sharp annual peaks, the magnitude of which could be 3–8 m, or 40–60% of the nominal regulation heights (Figs. 8–9). The annual peak accounted for 60% or more of the total variance in water level (Table 2; Ossjø, Aursunden, Store Bleikvatn), clearly emphasizing the tightly-controlled management under which these lakes are operated. Accordingly, the zero-frequency variance, or long-term 'noise', was insignificant (except for Byglandsfjord, the management schedules of which changed slightly during the 1970's).

The range measure spectra of the 'semi-natural' group contrasted those of the storage reservoirs (Fig. 8). Although their frequency distribution coincided, the individual peaks showed far lower amplitudes. Kilefjord and Venneslafjord had the flattest range spectra of the lakes, clearly demonstrating that their operational schedules led to a 'white-noise' random process of draw-downs.

Vangsvatn water levels had spectral characteristics intermediate to the 'storage reservoir' and the 'semi-natural' groups (Figs. 8–9). This lake also joined the 'storage reservoirs' when all lakes were ranked according to variance and range measures (Table 2).

Average period length, $\bar{T}_p$, featured a consistent pattern (Table 2). In particular, lakes operated on short-time schedules had very short periods (≤ 0.2 y), as also did the river-run Vangsvatn. Ranked by the criterion of averaged spectral periods, the lakes Tyrifjord and Maridalsvatn exhibited similarities to the storage reservoirs.

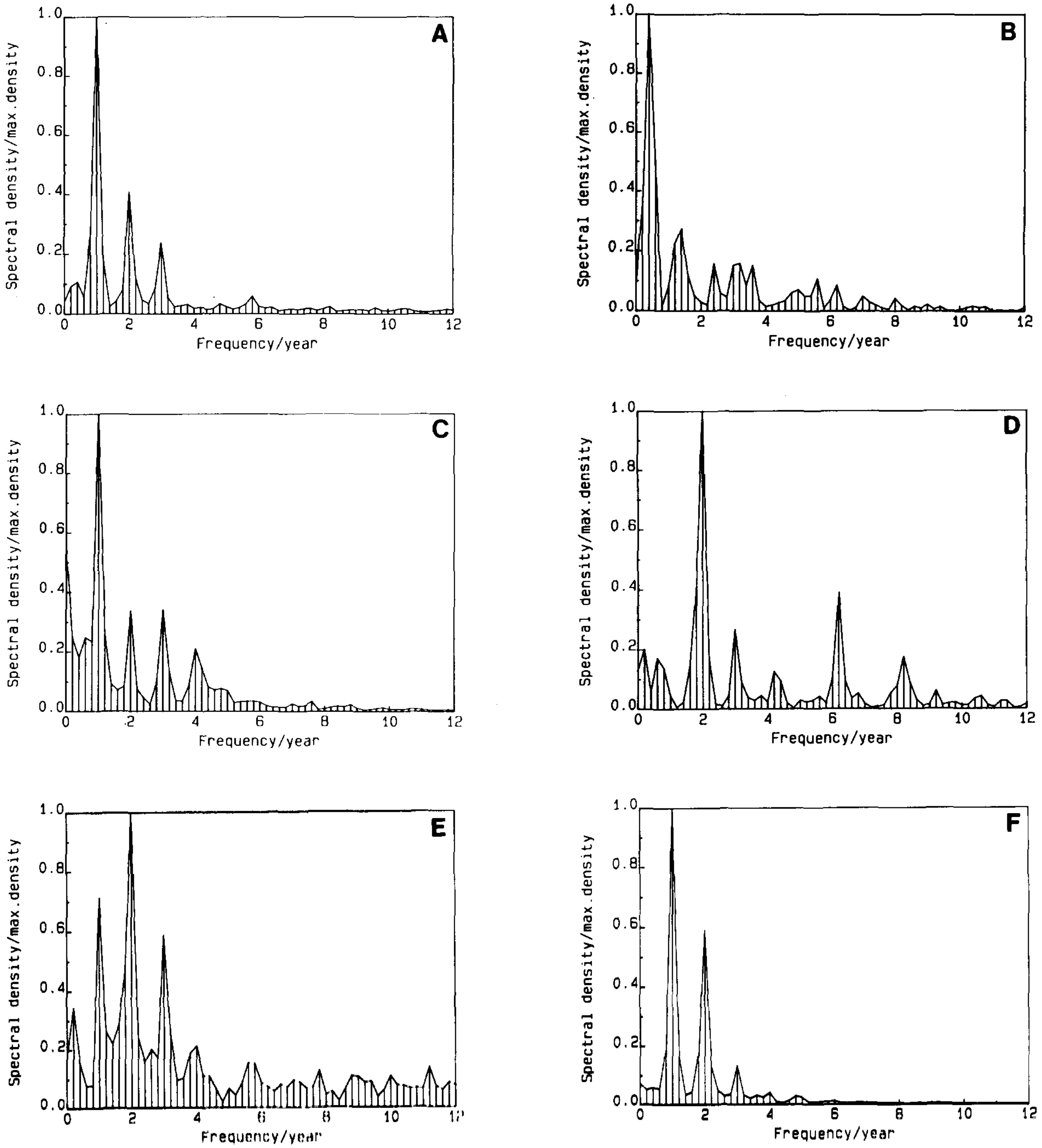

Fig. 6. Relativized spectral density (autovariance or power spectra) for representative lakes. See text for details. A: Vangsvatn, B: Maridalsvatn, C: Tyrifjord, D: Venneslafjord, E: Kilefjord, F: Breidvatn.

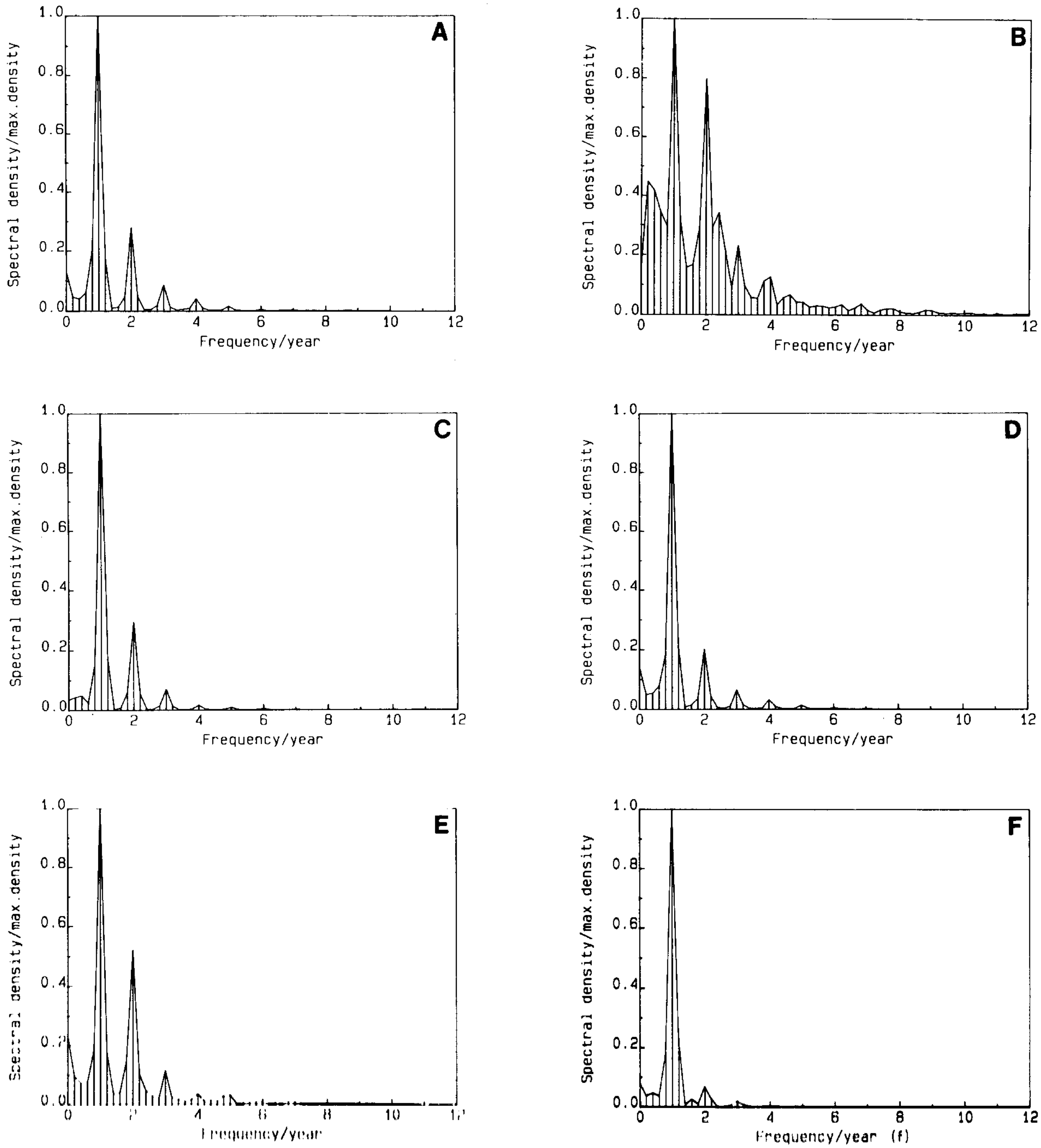

Fig. 7. Same as Fig. 6. A: Randsfjord, B: Byglandsfjord, C: Aursunden, D: Ossjø, E: Hartevatn, F: Store Bleikvatn.

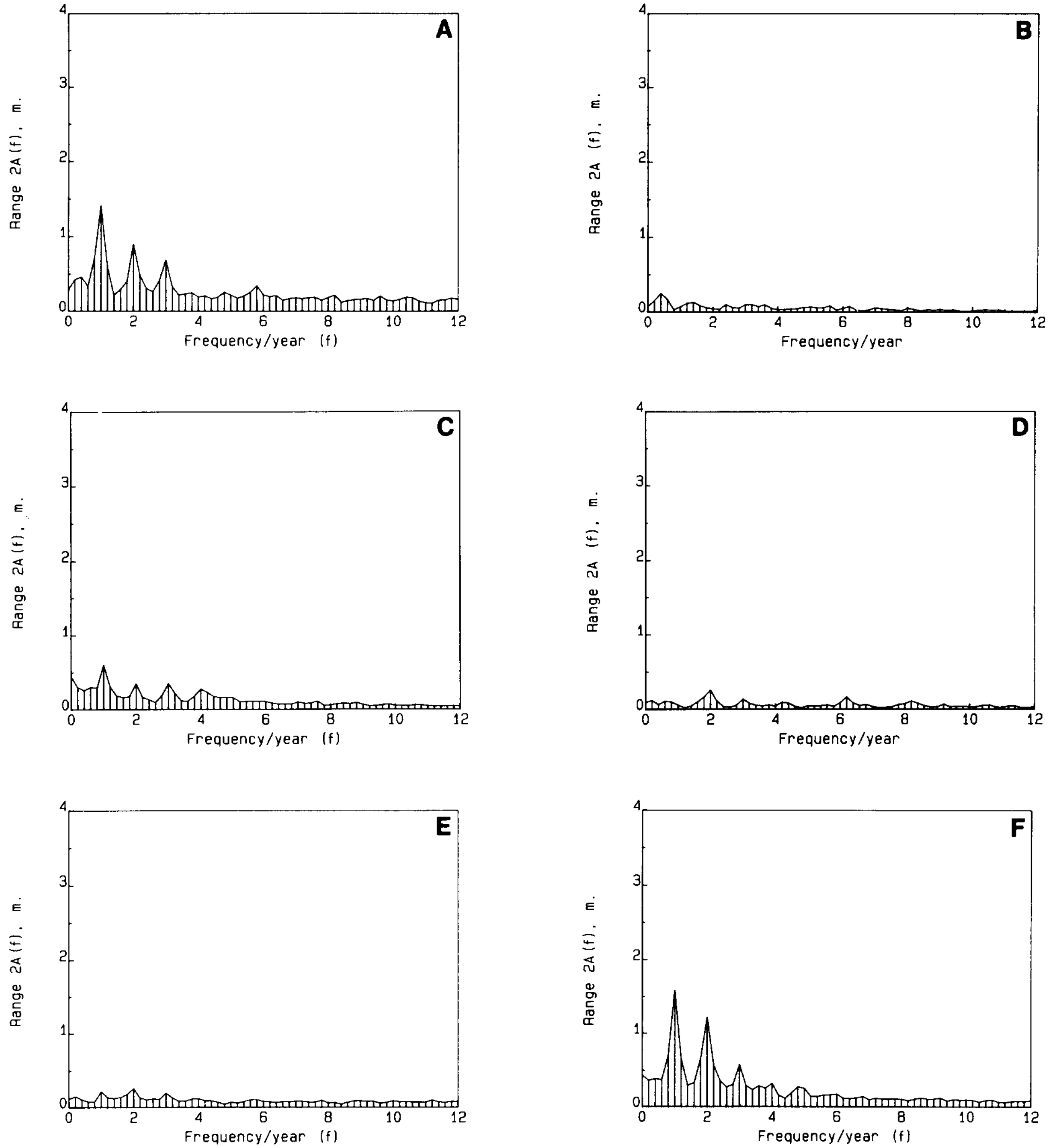

Fig. 8. Same as Fig. 6, but depicting the equivalent ranges of water levels, 2A [·] (refer to text for definition). A: Vangsvatn, B: Maridalsvatn, C: Tyrifjord, D: Venneslafjord, E: Kilefjord, F: Breidvatn.

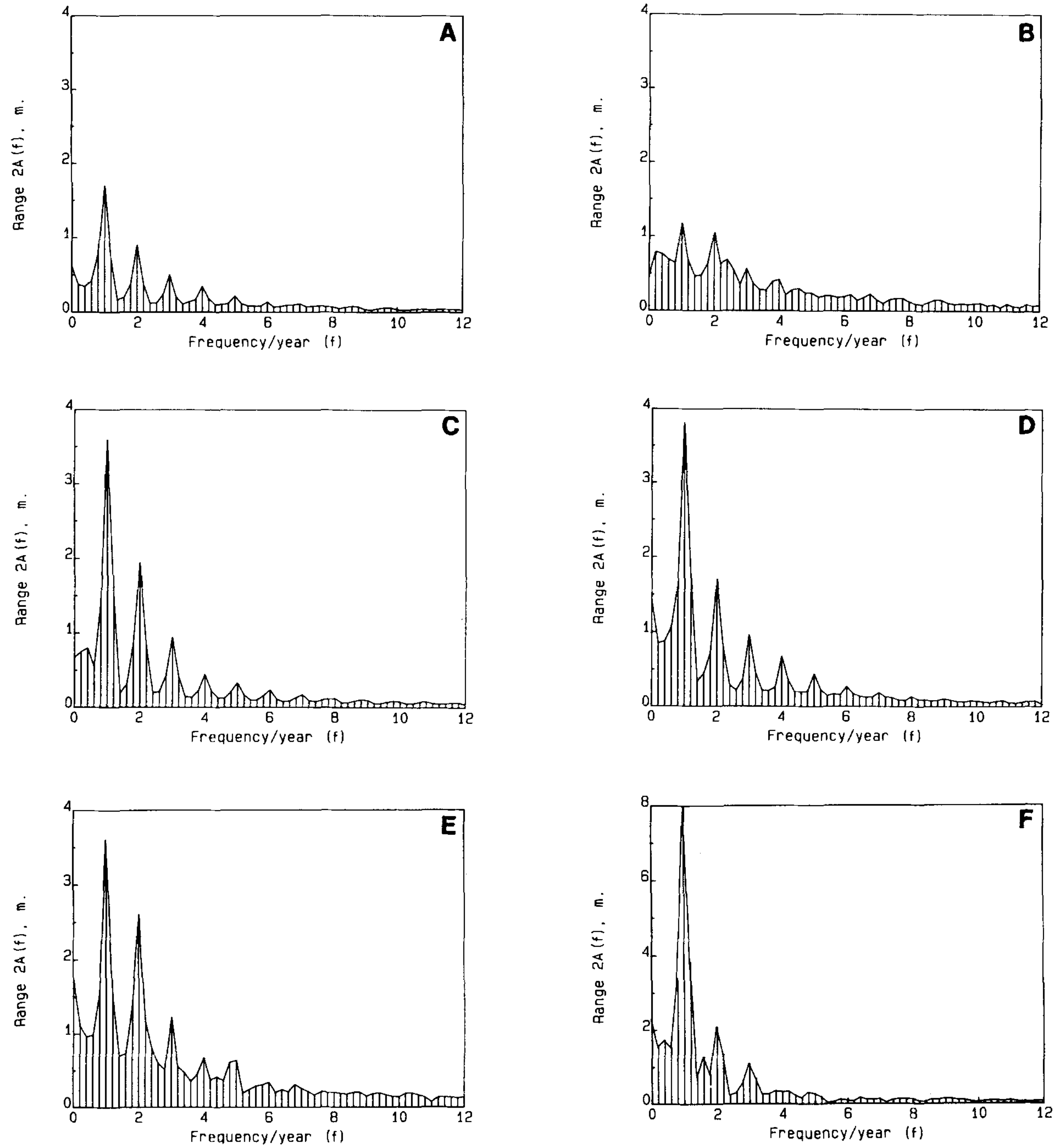

Fig. 9. Same as Fig. 8. A: Randsfjord, B: Byglandsfjord, C: Aursunden, D: Ossjø, E: Hartevatn, F: Store Bleikvatn (note: ordinate scale change).

Table 2. Overview of water-level fluctuations for some representative hydrolakes (H) and semi-natural (N, sN) lakes. Refer to text for details of concepts and to Table 5 for H, N, sN terms applied.

Lake		Variance*		Equivalent ranges**			Average period $\bar{T}_p$ (year)
		$\hat{\sigma}^2$ (m^2)	$\hat{\sigma}^2[f_0]$ (%)	$2\bar{A}_\infty$ (m)	$2\bar{A}[f_0]$ (m)	$2\bar{A}_{f0}$ (m)	
Store Bleikvatn	H3	14.20	78.2	10.66	7.99	9.41	0.923
Hartevatn	H3	5.08	42.2	6.37	3.59	4.63	0.542
Ossjø	H3	3.81	62.7	5.52	3.80	4.66	0.748
Aursunden	H3	3.22	64.1	5.08	3.58	4.09	0.702
Byglandsfjord§	H3	1.18	23.6	3.07	1.17	1.89	0.427
Vangsvatn	N1	0.99	32.9	2.82	1.41	1.75	0.192
Randsfjord	H3	0.78	58.6	2.50	1.70	2.07	0.658
Breidvatn	H3	0.75	56.0	2.45	1.58	1.84	0.414
Tyrifjord†	sN2	0.22	27.7	1.33	0.60	0.93	0.390
Kilefjord	H2	0.13	8.6	1.01	0.22	0.32	0.131
Venneslafjord	H2	0.08	0.3	0.81	0.10	0.22	0.134
Maridalsvatn	sN2	0.07	2.7	0.72	0.14	0.35	0.302

* f_0 = fundamental frequency ($= 1\ yr^{-1}$).

** [] single-band value, otherwise integrated up to given limit.

§ Operated in conjunction with Åraksfjord.

† Steinsfjord lake levels equal those of Tyrifjord.

Water-level fluctuations: Time domain analysis

An alternative to spectral representation of water-level features is provided by time-domain analysis, and in particular, by plotting the time series $W_* = \{w_*[t]\}$ as the corresponding percentiles over time in a stage hydrograph (Fig. 10). These percentiles represent conditional probability density estimates for $\{w_*[\tau \mid t = n\tau], n = 0, \ldots. T/\Delta\}$ where τ now is seasonal time (cyclic with period Δ). As found earlier, $v[z \mid \tau]$ for $z = 0$ has identical density to the seasonal $\{w_*[\tau]\}$ and hence its marginal distribution function is $P_v[\cdot]$.

The disadvantage of time-domain analysis is that out-of-phase data reduce information attainable by time-smearing. However, because the hydrolakes considered here are tightly operated, time-smearing is minimalized. An alternative would be hybrid domain analysis, e.g. complex demodulation (Brillinger, 1981).

Time-domain analysis highlighted an additional feature which discerned natural (e.g. Vangsvatn) and some hydro-electric lakes (e.g. Venneslafjord, Kilefjord) possessing more or less right-skewed pdf's, viz. the reversed pattern of high water levels in the hydrolakes. As depicted on Fig. 10, Venneslafjord had elevated winter-time lake levels, whereas Vangsvatn in contrast exhibited its lowest lake levels during winter.

Time-averaged depth D[·]

Water-level measures considered so far clearly pertain to the lake as an entity. However, measures relating to the vertical gradient can easily be calculated from eqn. (1). Such measures, e.g. time-averaged depths D[·], and ice-scour (IS[·], to be considered later on), obviously are Eulerian domain functions. In fact, D[·] is the simplest linear measure derivable from eqn. (1) and is given by,

$$D[z] = E\ \{v[z] \mid v \geq 0\} = \int_0^\infty h\ p_v[h + z]\ dh \qquad [6]$$

Figure 11 depicts the different shapes of D[z] profile for representative lake groups. Rørslett (1984) demonstrated the D-domain to be non-linear in z, as clearly evidenced by Fig. 11.

Because $p_v[\cdot]$ by definition is non-negative, eqn. (6) shows D[z] to be a monotone increasing function

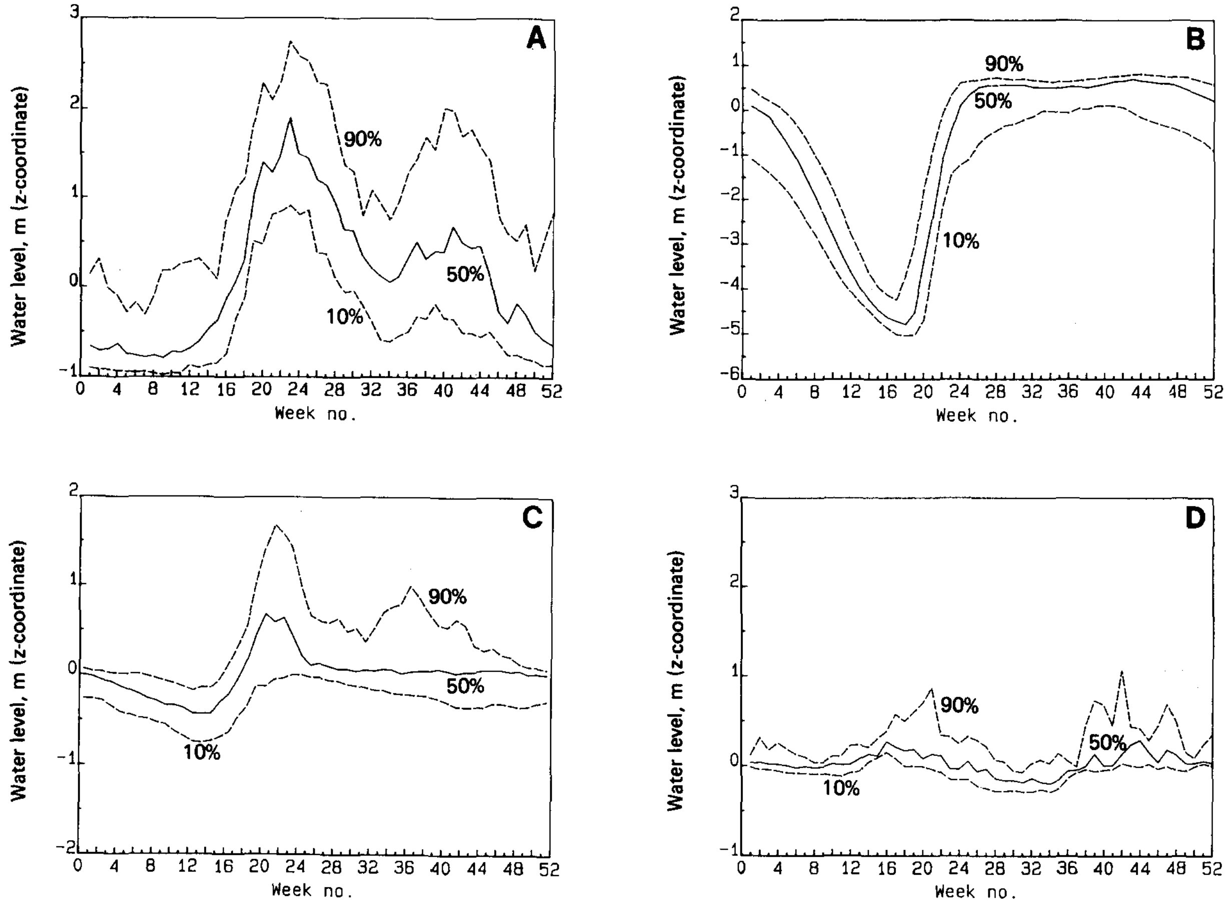

Fig. 10. Annual water levels, percentile distribution. Levels plotted as the corresponding z-scale variates. 10–, 50–(median), and 90–percentiles are indicated. Refer to text for details. Note ordinate scale changes. A: Vangsvatn, a non-manipulated lake; B: Aursunden, a storage-type hydrolake; C: Tyrifjord, a semi-natural lake; D: Venneslafjord, a hydrolake operated on short-time basis.

of z. Hence a unique inverse D^{-1} exists, such that D^{-1} {D[z]} = z. This enables a definite mapping from z- to D-domain, or vice versa. Although the information content of D- and z-domain coordinates by theory should be identical, the scope of D-coordinates is restricted to linear or nearly linear gradient functions (Rørslett, 1984, 1987a).

Physico-hydrochemical factors

Temperature

Norwegian inland waters seldomly attain maximum temperatures above ca. 20 °C. From the scanty data available on temperatures, all lakes reach at least 15 °C during the summer. Most of these lakes stratify during summer. Thermocline depths (Lagrangian coordinate domain) ranged from 10 to 25 m with large individual as well as seasonal variations (Table 3). Some river-run lakes are either too shallow (Flåren) or have insufficient residence time and mixing length (e.g. Venneslafjord) to stratify.

Internal waves in lakes generate significant short-time departures of thermocline layers (e.g. Mortimer, 1961, 1974). Thus, automated recording of (Lagrangian) temperature profiles from Tyrifjord, Randsfjord, and Vangsvatn demonstrated the existence of strong internal waves affecting the thermocline position (T. Tjomsland, pers. comm., 1986). Vertical excursions of the thermocline layers could

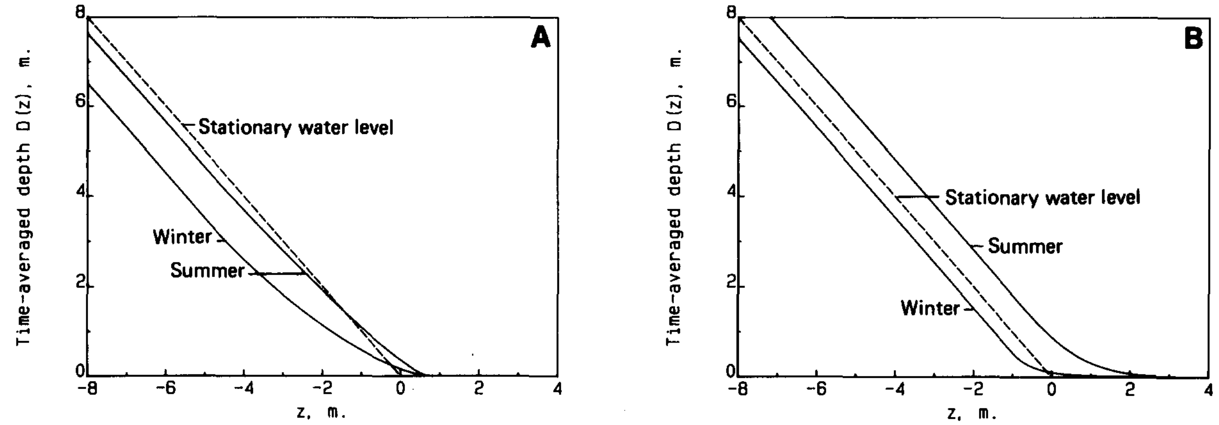

Fig. 11. Time-averaged depth, D[z], profiles from two lakes with extended water level alterations. A: Aursunden, a storage-type hydrolake, B: Vangsvatn, a natural lake.

exceed 5 m d^{-1} (Tyrifjord, Randsfjord). Holtan (1973) reported similar ranges from Mjøsa, the largest lake of Norway and operated for HEP use. These alterations of Lagrangian thermocline position would add significant random noise to the Eulerian domain temperature profiles. In conjunction with water-level fluctuations, the likely end effects are a smoothing of Eulerian temperature profiles. Eulerian domain temperature profiles from Tyrifjord supported this assumption, by exhibiting less

Table 3. Miscellaneous morphometric and hydrological data. Refer to text for discussion of concepts and terms applied.

Lake	Maximum depth (m)	Residence time (year)	Thermocline depth[1] (m)	Ice-cover period[2] (days)	Erosion depth[3] (m)
Venneslafjord	17	0.002	NA	<90	3 – 6
Vangsvatn	60	0.13	10 – 15	90 – 120	3 – 10
Lønavatn	26	0.02	10	90 – 120	3 – 10
Tyrifjord	296	2.6	15 – 25	90 – 120	5 – 20
Steinsfjord	24	4.6	10	140	5 – 10
Randsfjord	120	5.3	15 – 25	140	5 – 15
Maridalsvatn	45	0.5	5 – 15	150	4 – 9
Kilefjord	16		10	120	3 – 12
Byglandsfjord	167	0.6	15 – 20	120	>15
Åraksfjord	144	0.6	10 – 15	120	>10
Flåren	4	0.01	NA	140	<1
Store Bleikvatn	40	2.0	10	160	
Ossjø	117	2.7	10 – 20	150	
Bykil	>20		NA	140	<4
Aursunden	60	0.9	10 – 20	160	
Hartevatn	27	0.1	10 – 15	160	15 – 20
Breidvatn	>25	0.09	10 – 15	160	5 – 10

[1] Lagrangian coordinates (v).

[2] Estimated period, subject to large yearly variations.

[3] Time-averaged depth (D_e), Eulerian domain.

than 2 °C differences within the upmost 16 m vertical zone ($z = 0$ to -16 m, Rørslett, 1987c).

Erosion of lake floors and nearshore areas
Scouring of lake floors was observed on the photographic data, and could be attributed either to ice-scour or sublacustrine erosion. The erosional processes in a lacustrine environment are caused by a variety of factors, the elucidation of which would be well outside the scope of this paper. The topic is reviewed by Sly (1978) and within a wider framework by e.g. Komar (1976).

*Ice-scour*IS[·] The vertical distribution of the scour measure, IS[·], clearly reflected the schedules of draw-down and water-level management (Figs. 12–13). The storage reservoirs, viz. the lakes Ossjø, Aursunden, Hartevatn, and Breidvatn, had a bimodal scour pattern. This pattern reflects the high water levels at ice-on and the prevailing low draw-down levels. Because infilling and draw-down of these lakes were fairly rapid, ice-scour impact at intermediate z-levels decreased. The IS[·] distribution for Randsfjord resembled those mentioned above however, the secondary peak was less clearly defined. Byglandsfjord IS[·] influence extended to low z-levels, but did not show a defined secondary peak. Store Bleikvatn had significant IS[·] influence over more than 12 m of the vertical dimension, without the strongly peaked pattern featured by other reservoirs. In the field, ice-influenced scour regions of the storage reservoirs featured prominent stone or gravel ridges at their upper and lower limits (Cf. Fig. 13).

In contrast to the storage reservoirs, estimated ice-scour in the remaining lakes influenced only a narrow vertical zone, shown by a sharply peaking IS[·] function without appreciable side lobes (Fig. 12).

Lake bed and floor scouring Rørslett (1987c) described two broad categories of erosional signs reflecting scouring on the lake floors of Tyrifjord; (i) ripples, characteristic of shallow-water or sustained wave-mediated energy input; and (ii) pocketholes ('blow-outs') indicating excessive turbulence close to the lake floor. In Tyrifjord, erosional activity could be detected to time-averaged depth of more than 10 m, also at less exposed sites.

I selected the lower depth of observed erosional activity (D_e) at the most exposed site (if more than one site in a lake) as an indicator of vertical erosional range. All photographic observations of erosional phenomena (rippling, pocketing, striation, dislodged stones, sediment scars, slumping) were pooled for this analysis, and located to nearest 0.5 depth interval (D[z], time-averaged).

All lakes showed signs of sublacustrine erosion, often extending to quite substantial depths (Table 3). Shallow lakes, e.g. the weir basin Flåren, or smaller water bodies (Bykil, Venneslafjord), had less extended erosional ranges. No statistical correlation of D_e to extent of water-level fluctuations could be demonstrated (Spearman rank correlation $r_s = 0.01$, NS). However, D_e related significantly to lake area (Spearman's $r_s = 0.52$, $P < 0.05$). Additionally, there existed an overall agreement between observed downwards extension of erosional activity, and the thermocline position. Using mid-points of the thermocline intervals reported here (Table 3), a significant relationship to erosional depth could be demonstrated (Spearman's $r_s = 0.57$, $P < 0.05$).

Optics
Secchi disc readings varied from less than 3 m to well above 20 m (Table 4). Water clarity is an outstanding feature of the Setesdal lakes. Thus these lakes had Secchi disc readings from 7–10 m (Hartevatn, Venneslafjord) to 20–24 m (Byglandsfjord, Breidvatn). According to the data obtained by the Norwegian Institute for Water Research, Secchi readings exceeding 10 m are quite common in Norwegian soft inland waters. However, only a few pristine, medium- to high-altitude lakes are likely to attain readings in the 20–30 m range.

The mean (time- and depth-averaged) vertical attenuation coefficient, k_{PAR}, of my lakes ranged from 0.29 m^{-1} in the high-altitude lake, Breidvatn, to 0.80 m^{-1} in the humic lake, Ossjø. These values are well within ranges reported from oligotrophic lakes elsewhere in the world (Sand-Jensen & Søndergaard, 1981; Kirk, 1983; Rott, 1986). If anything, they are slightly higher than some values for oligotrophic lakes (e.g. the 0.1–0.3 range reported from pristine New Zealand water bodies; Howard-Williams & Vincent, 1984). However, being a statisti-

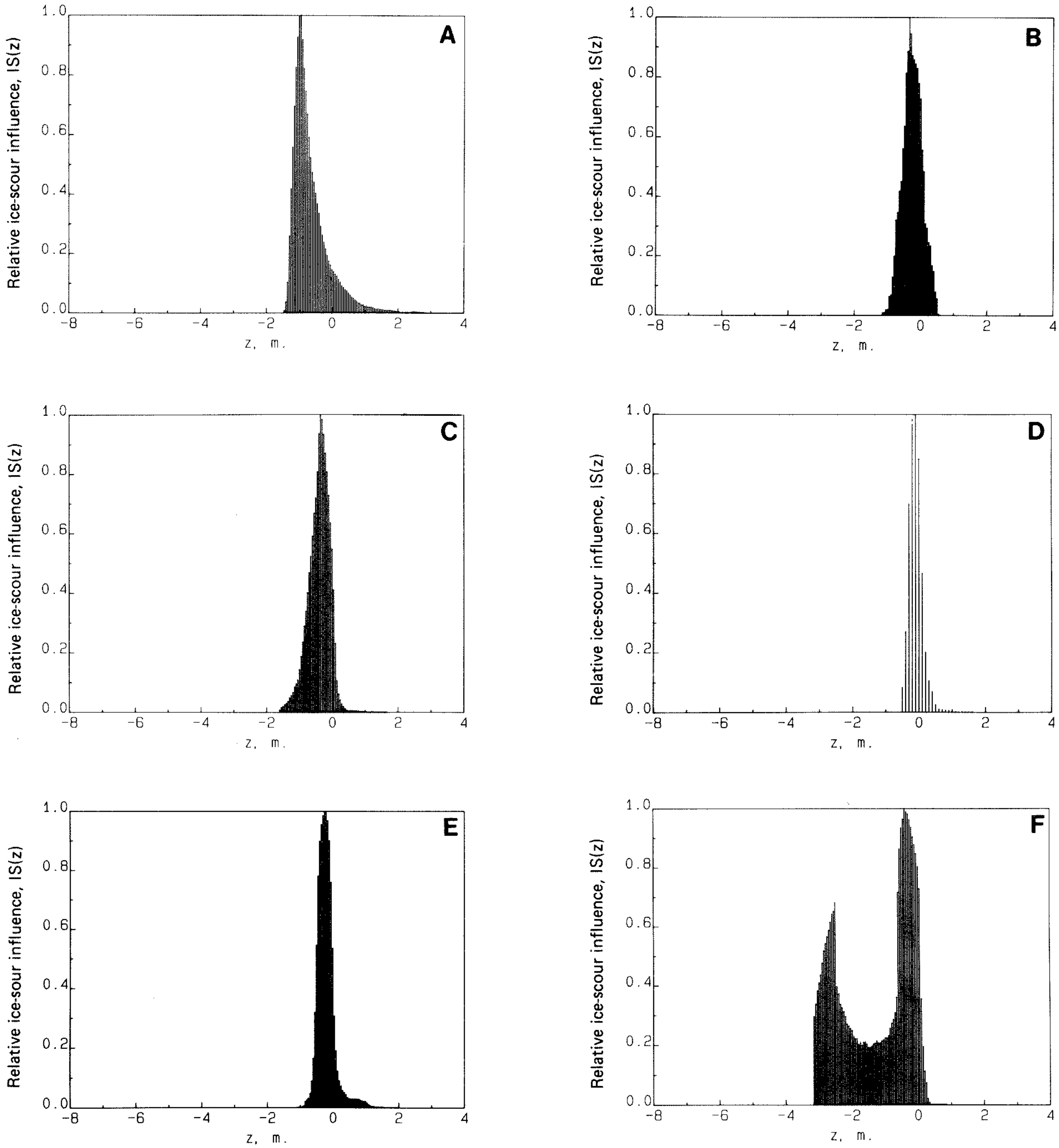

Fig. 12. Ice-scour influence, IS[z], distribution across the vertical (z−) gradient. Refer to text for definition of IS[·]. Ordinate scaled relative to the maximum IS[·]. A: Vangsvatn, B: Maridalsvatn, C: Tyrifjord, D: Venneslafjord, E: Kilefjord, F: Breidvatn.

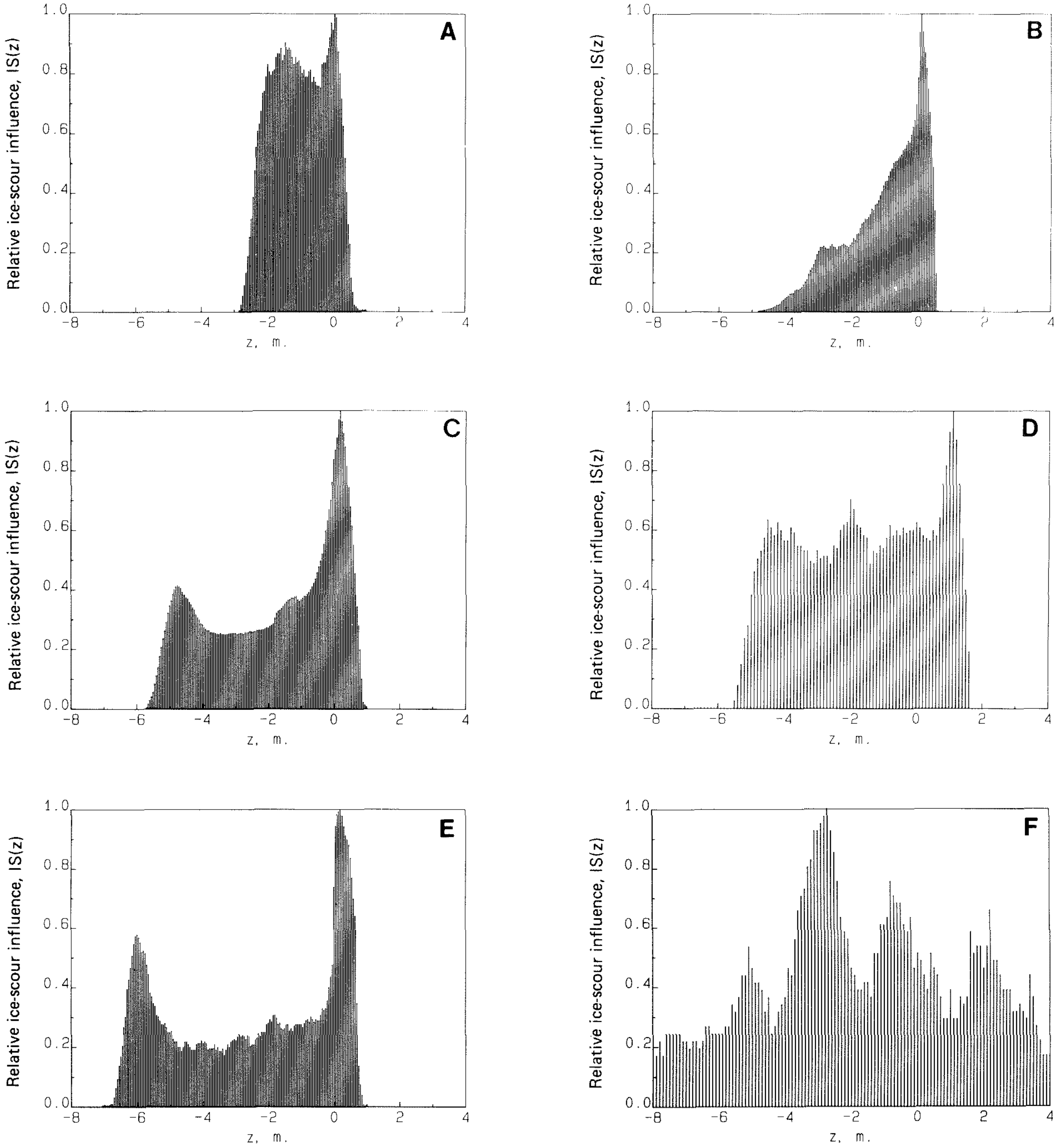

Fig. 13. Same as Fig. 12. A: Randsfjord, B: Byglandsfjord, C: Aursunden, D: Ossjø, E: Hartevatn, F: Store Bleikvatn.

Table 4. Optical and hydrochemical data from the investigated lakes. Compiled from data obtained by the Norwegian Institute for Water Research (NIVA) from 1976 to 1982. Data from central lake sites. Median (single values) or observed ranges given.

Lake	k_{PAR} (m^{-1})	Secchi depth (m)	pH	Conductivity (mS m^{-1})	HCO_3 (mEq m^{-3})	P (mg m^{-3})	N (mg m^{-3})
Venneslafjord	0.36	8–10	5.2–5.8	1.1–2.2	80	5	320
Vangsvatn	0.46	5–9	5.9–6.5	0.9–2.1		9	180
Lønavatn	-	5–9	5.9–6.5	0.9–1.7		6	170
Tyrifjord	0.53	5–10	7.0	3.2	180	7	400
Steinsfjord	0.58[1]	2–7	8.4	9.0	610	11	250
Randsfjord	0.54	4–9	7.0	3.8		5	450
Maridalsvatn	0.46	5–8	6.8	2.8	85	5	410
Kilefjord	0.35	9–12	5.2–5.8	1.1–1.7	45	5	190
Byglandsfjord	0.34	9–21	5.8–6.0	1.0–1.2	40	2	130
Åraksfjord	0.32	9–23	5.8–6.1	1.0–1.1	40	<2	140
Flåren	0.60	>4	5.7–6.3	1.1–2.8	50	5	150
Store Bleikvatn	-	9–11	7.3	4.1	280	3	160
Ossjø	0.80	3–6	6.3	1.9	90	7	280
Bykil	0.37	9–12	5.6–6.3	0.9–1.4	40	4	140
Aursunden	0.45	6–10	7.25	3.3	320	5	250
Hartevatn	0.46	7–13	6.0–6.4	0.9–1.3	70	4	120
Breidvatn	0.29	10–24	6.2–6.6	0.9–1.1	70	3	140

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[1] Steinsfjord value decreased to 0.54 when data from 1983–84 were included.

cal best-fit composite of linear as well as non-linear attenuation models (cf., Rørslett, 1987a), k_{PAR} values reported here are not quite compatible with those of the other authors.

Hydrochemistry

Averaged hydrochemical data are presented in Table 4. The studied lakes, except for Steinsfjord, clearly are soft-water lakes poor in nutrients and can be designated as oligotrophic water bodies. These lakes had conductivity well below 5 mS m^{-1}, and in that respect, they are quite typical of most pristine Norwegian lakes (Norwegian Institute for Water Research, unpublished data). Steinsfjord, Store Bleikvatn, and Aursunden are partly underlain by calcareous bedrock, and feature slightly elevated pH and alkalinity values. The pH of Steinsfjord also rose due to enhanced primary production by the submerged species, *Elodea canadensis* (Rørslett *et al.*, 1986).

The Setesdal lakes, in particular Venneslafjord and Kilefjord, are somewhat impacted by acid precipitation. Thus, the pH of these lakes is reportedly lowered 0.5 pH-units or more from the previous 5.5–6.0 range (Norwegian Institute for Water Research, unpublished data; also see Wright, 1984). The decline in pH is associated with a marked expansion of *Sphagnum* spp., enhanced periphyton productivity, and an increase of acid-tolerant species such as *Juncus bulbosus* L. (Rørslett, in prep.). These changes are quite similar to those reported from Swedish lakes (Grahn, 1985).

Discussion

Perspectives

The physical impacts of lake regulation can be severe (e.g. Baxter, 1977; Bodaly *et al.*, 1984; Canter, 1985). Impacts should also be more or less predictable in advance (Hecky *et al.*, 1984), at least to hydropower engineers. The response of the impacted lake ecosystem divides into the transient response, expected to last for one or more decades (Cf., Nilsson, 1981; Hecky, 1984), and the persistent (long-term) response. The time-scale of the response exceeds greatly that of most biota inhabiting the impacted ecosystem. Although no generally accepted definitions of ecosystem stress or disturbance exist (Grime, 1979; Huston, 1979; Nisbet & Gurney, 1982; Pimm, 1984; Gerritsen & Patten, 1985; Rykiel, 1985), it is widely accepted that large and randomly occurring departures of system state variables from their average seasonal values tend to destabilize the ecosystem. Lake regulation clearly bears on these theoretical concepts (cf., Lindström, 1973). The impacts of a fluctuating water level combine aspects of ecosystem disturbance and stress, e.g. range of fluctuation (magnitude or intensity of stress-mediated disturbance, perturbations), ice-scour drawdowns (severity of disturbance) and lake level management schedules (predictability of stress or disturbance, stress avoidance, selection strategies). When multipurpose reservoirs are considered, the issue is further complicated by an enhanced irregularity of water-level alterations.

The vertical gradient is a major determinant of macrophyte occurrence in aquatic habitats (Hutchinson, 1975). This complex gradient is often associated to a gradient of increasing depths (Spence, 1982). Hydropower development can substantially alter the timing and realized ranges of water-level fluctuation (Rørslett, 1984). In impacted hydrolakes, depth-related factors should be interpreted within a probabilistic framework (Rørslett, 1987a). This is preferably accomplished by applying Eulerian (z) coordinates instead of the more traditionally used Lagrangian (v) coordinates, as formulated in eqn. (1). One easy way to distinguish these approaches is by recognizing that all depth measurements which use the instantaneous lake surface as a reference point, are Lagrangian coordinates (v); while any 'depths' corrected for the position of current lake level are Eulerian coordinates (z). The median water level should be used as a reference datum for water stages (Rørslett, 1984); level references then can be directly applied to eqn. (1) for evaluating any vertical gradient function.

The impression emerging from numerous papers and reports dealing with hydropower schemes, is that limnologists are preoccupied with Lagrangian domain analysis for their water quality variables. Secondly, as a consequence of this approach, the tendency is to treat reservoirs as man-made equivalents to natural lacustrine systems, which could be fallacious (cf., Ryder, 1978). The attitudes of biologists depend on their research fields; thus fishery biologists are Lagrangian-oriented (e.g. Aass, 1973), whereas botanists appreciate Eulerian domains, at least indirectly (Nilsson, 1981). However, biologists engaged in hydropower impact assessments join force by emphasizing the 'stressed nature' of a hydroelectric lake (Grimås, 1962; Wassén, 1966; Lindström, 1973; Nilsson, 1981; Rørslett, 1984, 1985a; Grelsson, 1986). The scaling of that implied stress is not attempted, however, except in the vaguest terms. So the concept of a hydrolake as a stressed system is not backed up with any possibility of ranking the water bodies according to defined 'stress' measures.

Environmental features

In a broad sense, the hydrolakes reported on here are similar, hydrochemically speaking, to natural Norwegian lakes. Because before-impact hydrochemistry data are virtually non-existent, it is next to impossible to ascertain the effects caused by current hydropower schemes (if any). For a Swedish reservoir, Rohde (1964) claimed that impoundment led to insignificant changes in several hydrochemical variables when initial transients had decayed. New Zealand research (e.g. Magadza, 1979; Coulter *et al.*, 1983) might support that conclusion, but evidence produced there was largely circumstantial. Following an impoundment stage, a surge of terrestrial-originated material is expected, the decomposition of which could induce at least transient changes in reservoir hydrochemistry (Baxter, 1977; Vogt, 1978; Godshalk & Barko, 1985).

Ice-scour generally is considered to be of paramount importance for the zonation of Scandinavian river- and lakeside vegetation (Quennerstedt, 1958; Lohammar, 1965; Wassén, 1966; Hutchinson, 1975; Nilsson, 1981; Rørslett, 1984, 1985a). As for the lake floor and shorelines, the abrading nature of ice-scour is combined with an efficient pushing and sorting of the sediments (Hutchinson, 1957). The adverse influence of this activity to rooted macrophytes is well documented in the Scandinavian literature (Thunmark, 1931; Lohammar, 1965; Wassén, 1966), but is evaluated mainly in qualitative terms.

Data from this paper strongly suggest ice-scour pattern to be definable in semi-quantitative terms. Thus, Rørslett (1984, 1987c) related the cumulative probability of ice-scour to upslope limits of the submerged macrophyte, *Isoëtes lacustris* L. For the Setesdal lakes, Rørslett (1985a) demonstrated that amphibious species featuring annual life-cycles or opportunistic strategies, could survive within less intense scour regions, the extent and position of which were well predicted by the IS[·] measure.

Wind-mediated erosional activity likely is a major feature of inland waters (Smith & Sinclair, 1972; Johnson, 1980; Håkanson, 1981, 1982). However, freshwater lakes in general feature low-energy wave regimes when compared to marine conditions (Sly, 1978). Either wind duration, or the maximum fetch (of all but the largest lakes, cf. Liu, 1985) potentially could limit wave action.

Håkanson (1977) established an empirical diagram ('ETA'-diagram) describing the relationship between sediment features and wave-mediated erosion. The ETA-diagram divides lake floors into the erosion ('E'), transport ('T') or accumulation ('A') zones. Although derived for fine-grained sediments only, the ETA-diagram relates favourably to simulated erosional processes (e.g. Johnson, 1980) as well as actual field observations of erosional phenomena (e.g. Rørslett, 1987c). The ETA-diagram is developed in a Lagrangian domain and its applicability to lakes with significant water-level fluctuation is unknown (Rørslett, 1987c). Empirical relationships between thermocline depth v_{th} (Lagrangian domain) and lake fetch have been reported (Ragotzkie, 1978; Patalas, 1984) and conform to square-root or power functions of fetch vs. v_{th}. It can be inferred that these relationships would result in broadly similar patterns to those exhibited by the Håkanson ETA-diagram.

Structures such as offshore bars and shallow foreshore shelfs develop on natural shorelines, thus mitigating or dissipating the energy mediated by incoming waves (Komar, 1976). In the context of fluctuating water levels, ice-scour adds a new and detrimental dimension to the erosional impact of reservoir shorelines and shallows (Newbury & McCullough, 1984; Kuusisto, 1985). The destructive impact of breaking waves in shorelines in newly incepted impoundments and reservoirs declines in its importances as shores are denuded of finer material (Kachugin, 1966; Kondrachev, 1966; Cyberski, 1973; Newbury & McCullough, 1984; Grelsson, 1986) and restabilization of the shore-lines takes place. However, the transient impact of the eroding processes could last for decades (Hecky & McCullough, 1984). Alteration of an established lake level management scheme would reinititate nearshore erosion (Grimås, 1962; Rustamov & Kchalilov, 1973; Aass, 1986; Kirk & Henriques, 1986).

Sublacustrine erosion, exhibited by all lakes in this study, would be expected from either thermocline excursions or expenditure of wave-mediated energy (Mortimer, 1961, 1964; Sly, 1978; Håkanson, 1981; Kirk & Henriques, 1986). This aspect of deep-water habitat disturbance largely has been neglected by aquatic biologists, although the effects of shallow-water wave action are recognized (e.g. Spence, 1982). Instability of offshore faces relates significantly to their steepness (Håkanson, 1981, 1982) and also to increasing wind fetch (Komar, 1976; Kirk & Henriques, 1986). Several studies document that enlarged water-level fluctuations, and in particular when combined by extended drawdowns, enhance erosion, landslips, and slumping of offshore faces and foreshore shelves (Matarzin & Pechorkin, 1973; Komar, 1976; Canter, 1985; Aass, 1986; Kirk & Henriques, 1986).

Recently, the underwater light field is emerging as a major determinant of macrophyte performance. Research by many workers (e.g. Spence, 1982; Canfield *et al.*, 1985; Chambers & Kalff, 1985; Rørslett, 1985b; Duarte *et al.*, 1986) demonstrate broad relationships between light parameters, and macrophyte biomass and extension. Effects of fluctuating lake levels are not generally considered in these regional studies, although water levels are almost certain to be variable in the geographic regions dealt with. Neither are the stochastic properties of underwater light commonly addressed.

Impoundment of natural lakes generally decreases vertical light penetration (Hecky, 1984). This effect gradually declines in importance as the shore and near-shore regions are eroded and parental bedrock exposed (Hecky & McCullough, 1984). Rørslett (1987a) demonstrated that the underwater light field could be described as a stochastic process, and obtained the mean and variance of this process valid for clear-water lakes. The Secchi disc readings related significantly to the attenuation integral but were fairly imprecise as predictors of vertical attenuation (Rørslett, 1987a). Under the stochastic model, it is feasible to estimate the vertical distribution of light field parameters. Impact of fluctuating water levels on underwater light regime can be assessed in the Eulerian domain (clearly, a Lagrangian analysis here would be inappropriate). Rørslett (1984, 1985b) performed that analysis for Tyrifjord and Hartevatn, and found elevated probabilities of low-light conditions at all z-levels. The stochastic nature of the underwater light field is supported by models of spatial survival niches (Rørslett, 1987b, 1987d) and evidence for transient deep-water niches (Rørslett & Agami, 1987). The influence of regulation would exacerbate mortality mediated by critical thresholds of low light (Rørslett, 1985b, 1987d).

Water-level fluctuations: Overview

A prime objective of the present study is to identify inherent features of the regulated lakes. As for hydrology, it proved quite difficult to establish generally valid criteria specific to such man-made water-level schedules.

Excepting Store Bleikvatn with its 21.5 m legislated lake level range, the lakes studied fall into the 0 – 9.9 m regulation height class, which comprises some 45% of Norwegian hydrolakes, and in that respect they clearly are representative of such waters (see the Introduction). Whether they also are typical in other aspects cannot be elaborated, because information on the geographical, morphometrical, and hydrological details of hydrolakes generally are nonexistent in Norway.

The water-level schemes of the lakes studied are mostly old, dating back to the 1920's or even earlier. The newest schemes to commence operation are at least 20 years old (Kilefjord, early 1950's; Store Bleikvatn, ca. 1965). Hence, these lakes should no longer feature transient stages of the regulation impact. The data presented evidenced the validity of this assumption. In fact, the investigated lakes had no outstanding features allowing discrimination from non-regulated lakes. Excepting very strongly regulated Norwegian lakes (regulation heights from say 8 – 10 m and up to 140 m), the water-level ranges found in my regulated lakes overlapped those of the non-managed water bodies. So the (nominal) height of regulation *per se* is not valid as a distinct criterion for distinguishing regulation-impacted lakes and non-regulated lakes.

Combining information from the alternative approaches pursued, the following general trends emerge. Firstly, lake levels can be extremely variable, even for non-manipulated lakes. Secondly, annual mean ranges are poor descriptive statistics when water-level fluctuations are concerned. Equivalent range measures, $2\bar{A}[\cdot]$ derived from frequency domain analysis, clearly are preferable. However, these measures do not provide an exhaustive description of lake levels, and should be augmented by e.g. time domain analysis. Thirdly, the initial grouping of lakes according to origin and HEP operational schedule, e.g. 'semi-natural', 'short-time regulated' and 'storage reservoirs' objects largely coincides with the patterns derivable from hydrology. However, even a clearly natural lake such as Vangsvatn could easily be misidentified as a hydrolake. Thus the importance of a multidimensional approach to habitat classification should be emphasized. By combining available hydrological and morphological features, a tentative classification of hydrolakes and their non-operated counterparts seems feasible (see Table 5).

This classification supports the noted tendency for hydrolakes to combine features otherwise not found in natural water bodies. Thus, the lakes belonging to the 'storage reservoir' (H3) group could always be picked out by their unique combination of a left-skewed water-level pdf and an left-extended, often doubly-peaked, ice-scour IS[·] vertical distribution.

The 'semi-natural' group as defined earlied comprised lakes in their (nearly) pristine state, as well as less intensively managed waters. By dividing this group as shown in Table 5, the differences between natural (N1, N2) and man-influenced lakes (H2) are enhanced. It is seen that the high winter water levels are a feature generally absent from Norwegian natural lakes. As for extent of lake level alterations, no sharp limit exists between the N-groups and H2

Table 5. Tentative classification of hydro-electric and natural water bodies. See text for details of concepts and terms applied.

Object type (origin)	Lake features				
	Through-flow-time	Water level range[1]	Freq. band[2]	Winter levels	Pdf shape
Hydrolakes (H)					
H1 Oscillating (impoundments)	Very short	small	HF (≥ 24)	high	1(2)-peaked (symmetric?)
H2 Intermediate (reservoirs)	Mainly short	small to medium	2 – 24	high	1-peaked ± right-skewed
H3 Storage (reservoirs)	Short to long	small to v. large	LF (≤ 5)	draw-down	(1)2-peaked left-skewed
Natural lakes (N)[3]					
N1 River-run (often small)	Short	small to large	LF (≤ 12)	low	1-peaked right-skewed
N2 Lacustrine (larger waters)	Often long	small to medium	LF (< 4)	low	1-peaked ± symmetric

[1] Actual values contingent upon frequencies of water-level fluctuations. Rough approximations are: small = ≤ 2 m, medium = 2 – 4 m, large = 4 – 8 m, very large = 8 – 100+ m.

[2] Frequencies as yr^{-1}. LF = low frequency, HF = high frequency band prevailing.

[3] Prefix 's', e.g. sN1, indicates a lake with artificial altered level schedules, the extent of which is largely contained within the 'natural' boundaries.

group. Hydrolakes in category H2 invariable demonstrate significant short-time fluctuations of lake levels, owing to their operational schedule.

A further group, 'oscillating levels' (H1) is delineated in Table 5. Such lakes, featuring significant high-frequency variance ($f > 200\ \text{yr}^{-1}$) are alluded to by e.g. Granju *et al.* (1973) and Nilsson (1984); these lakes or reservoirs clearly have to be riverine. Although these lakes also are present in Norway, mainly in conjunction with impoundments by control structures on rivers, insufficient data preclude assessing their frequency of occurrence amongst Norwegian hydrolakes.

The hydrolake categories of Table 5 form a habitat gradient from lake level regimes with high- (H1) to low-frequency (H3) dominance. Concomitantly, there are differences of water level ranges encountered within these groups. Taking the averaged measures, $2\bar{A}_{\infty}$ and $\bar{T}_p$ as indicators of 'disturbance' and 'stress', respectively, Fig. 14 depicts a pattern for hydrolakes and natural lakes of inherent interest. However, it should be pointed out that the applied statistics have to be interpreted within a descriptive framework, and moreover, they relate to state changes (aquatic-terrestrial) of the system only.

On the average, natural lakes tend to have less extended level fluctuations when time periods grow longer, or in other words, alterations of level are less predictable. However, the intensity of level alterations (i.e. prevailing frequencies) concomitantly declines. Thus disturbance and stress aspects are largely mitigated for these water bodies. River-run natural lakes show clear affinities to the intermediate (H2) hydrolake group, and actually can only be clearly defined on their low winter levels. Evidently, high-range tidal systems qualify as natural counterparts to at least one group of hydrolakes (H1). However, there is no natural selection for equivalent intertidal strategies among freshwater lake biota.

Conclusions and recommendations

Hydro-electric lakes have different origins, operating schedules, and water-level management. They may or may not comply to the concept of a reservoir in its strict sense, i.e. an impoundment or storage lake; they can even have lake levels contained within the pre-development range. Thus the noted tendency to unite such water bodies within concepts of 'reservoirs' or 'man-made lakes' is fallacious and should be discontinued. The prevailing physical nature of the impacts should be emphasized. This study identified water-level schedules, underwater light, and erosional processes, as major environmental features of the hydrolakes.

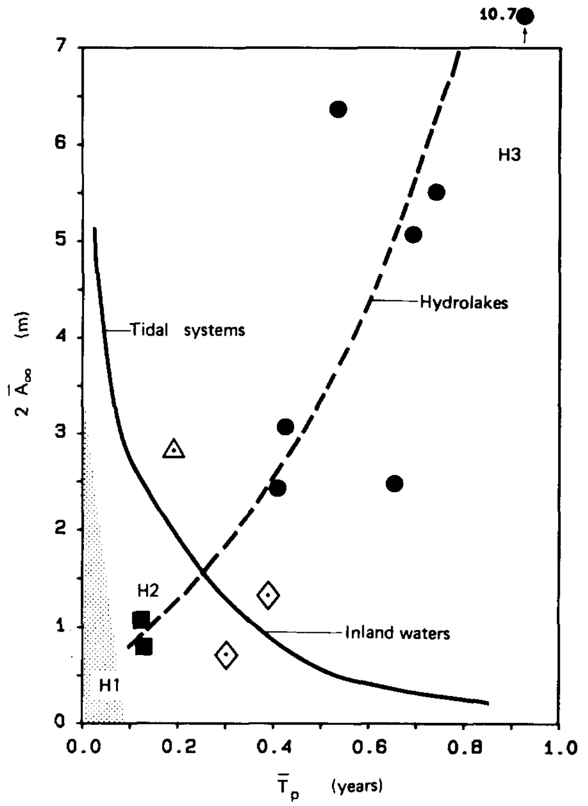

Fig. 14. Depiction of a simplified model for disturbance vs. stress patterns in natural and man-impacted lake systems. Disturbance represented by alteration of lake levels, here indicated by $2\bar{A}_\infty$; stress represented by intensity of level fluctuations (or duration of adverse events), here indicated by $\bar{T}_p$ (low 'stress' given by large values of $\bar{T}_p$).

Legends

Open symbols denote natural lakes while closed symbols indicate hydrolakes. Circles: Hydrolake type H3; Squares: Hydrolakes type H2; Shaded area: Suggested domain for hydrolakes type H1; Triangles: Natural (river-run) lake type N1; Diamonds: Natural or semi-natural lakes types N2 and sN2.

No single criterion can delineate the water-level regime of a managed lake from that of a natural lake. The magnitude, or averaged range, of observed water-level fluctuations is insufficient by itself, at least for annual ranges up to 6–7 m. In fact, the water-level statistics commonly used (actual or nominal ranges) poorly describe the actual water-level regime of a hydrolake. Augmented statistics are presented as alternatives here. Time series approaches, e.g. spectral analysis and time domain analysis, elucidate differences, some of which were otherwise not apparent, between hydrological regimes of the studied lakes.

By applying a multi-aspect habitat classification, broad categories of hydrolakes can be defined. Consistent use of the proposed lake terms would facilitate future research, in which the ecological stress and disturbance aspects of hydrolakes should be addressed. Thus, hydrolakes could be appropriate testing-grounds for existing and emerging ecological theories. However, in order to enable these objectives, a number of prerequisites are needed.

Future research should carefully evaluate existing hydrological data, or even initiate the necessary hydrological gauging sites whenever feasible. Preferably, hydrological analysis should precede biological assessment and field studies, and the hydrological classification conferred to the biologists in advance of their planning of field sampling and strategies. Biologists should distinguish between fixed- and moving-coordinate systems in descriptions of lake biota distribution patterns; furthermore, they should state clearly the system applied and stress the statistically defined boundary between aquatic and terrestrial habitats, i.e. median lake level.

Preferably, biologists should adopt fixed-coordinate analysis for all types of benthic communities. Moreover, they should ensure that all limnological data (which nearly always are acquired within a Lagrangian frame) are properly mapped into the Eulerian domain before attempting any correlation between biota and environmental factors. Finally, biologists should attempt to develop conceptual, or better, causal models of expected changes following hydropower development, and evaluate the success of these predictions by after-impact studies.

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