Scientific Research Publishing

Open Journal of Modern Hydrology, 2025, 15(2), 159-175
https://www.scirp.org/journal/ojmh
ISSN Online: 2163-0496
ISSN Print: 2163-0461

Seasonal and Spatio-Temporal Distribution of Nutrients in the Hula Valley after Drainage: B: Phosphorus

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How to cite this paper: Gophen, M. (2025) Seasonal and Spatio-Temporal Distribution of Nutrients in the Hula Valley after Drainage: B: Phosphorus. *Open Journal of Modern Hydrology*, **15**, 159-175.
https://doi.org/10.4236/ojmh.2025.152011

Received: December 14, 2024
Accepted: April 4, 2025
Published: April 7, 2025

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Abstract

Among several soil types in the Hula Valley, Peat soil occupies a significant part of the agricultural cultivation area, and Phosphorus is a critical constituent. Cultivation in the Hula Peat land is a critical achievement, whereas phosphorus migration southward into Lake Kinneret is of national concern. Consequently, phosphorus resource sites and spatiotemporal distribution and fluctuations of phosphoric substances are critical for the design of effective management strategies. A long-term record (1994-2024) of spatiotemporal concentration fluctuations in relation to climate (rain capacity) conditions was statistically evaluated. Results emphasized soil moisture as a significant factor affecting phosphorus dynamics. This paper examines the impact of soil moisture on Phosphorus dynamics and management strategies in the post-drainage Hula Valley. The interplay between natural climate variability (rainfall fluctuations) and human activities (irrigation, fertilization) predominantly controls soil moisture levels and consequently affects Phosphorus migration. Four conceptual mechanisms of Phosphorus migration are discussed: Microbial Enzymatic Concept (MEC), Geochemical Moisture Redox Concept (MRC), Alternate Wetting Dryness Concept (WDC), and Agricultural Fertilization Concept (AFC). The previous Hula wetlands and old Lake Hula are present, after drainage, under agricultural management, in which allocation and supply of irrigated water and fertilization regimes are dictated by crop demands. The objective of this paper is to optimize the management design for cultivation practices and prevention of pollutant leakage into Lake Kinneret.

Keywords

Hula Valley, Peat, Phosphorus, Moisture, Dryness, Redox

1. Introduction

The ecological conditions reforms in the Hula Valley during the last 100 years initiated significant involvement of Nitrogen and Phosphorus cycle processes. During the pre-drainage period, the Hula Valley's swampy wetlands were densely covered with lush vegetation of emergent and submerged aquatic plants. Suspended particles and plant debris settled and accumulated on the bottom, creating a massive deposit of organic matter, namely Peat under anaerobic conditions. The anaerobic conditions dictated the reductive formation of Nitrogen (Ammonia) and Peat particles linked to Phosphorus. After drainage (1957), the organic matter content within the surface-shallowest layer was exposed to aerobic conditions. In deeper layers, aerobic conditions were gradually diminished and transferred into reductive anaerobic situations. It is therefore likely that interactions between Phosphorus compounds and oxygen or mixed oxidize conditions are distributed hypsometrically within the Peat soil matter. The research on the impact of man-made changes on particles linked to migrative phosphorus within Peat soil in the Hula Valley was carried out. It is based on the evaluation of long-term records (1994-2024) of Phosphorus distribution within the Peat soil-drained waters accompanied by experimental study.

The ecological studies that accompanied research of wetlands drainage and agricultural landscape conservation, particularly in Peat Land, are presently a worldwide common practice. The objective of this study is aimed at spatial and temporal range definitions of Nitrogen and Phosphorus [1]-[3] involvement processes as supportive tools for the design of agricultural management accompanied by Kinneret water quality protection. Soil features in the Hula Valley are highly variated and are divided into three major groups: mineral lake sediments, Peat, and transitions. Peat soil samples were collected from two outlets: sampling Station No. 57, representing the central Peat soil block, and sampling station No. 73, representing the eastern Peat soil block. Both outlets drain into LAH. These samples provide an optimal representation of the porewater content in their respective blocks.

Recently, a study on the phosphorus (P) content of peat soils was published [4] (**Table 1**).

Table 1. Percentage (%) and concentration (mg/Kg) composition of the upper 0 - 30 cm layer of soil types properties in the Hula Valley: Peat—northern Peat block; Transition—central and east-central Peat blocks; Mineral—southern block [4].

Soil Type	pH	Total Lime (%)	Organic Matter (%)	"Olsen" P mg/kg
Peat	7.2	4.1	11	19.6
Peat	7.9	8.6	5.7	35.9
Transition	7.7	18.2	9	16.8
Transition	7.4	23.7	10.7	27
Mineral	7.7	64.3	7.4	21.2

Documented data [2] indicated organic carbon content (%) of 10 - 19, 5 - 16, and 3.3 - 10.4 in Peat soil, Transition land soil, and Mineral (lake sediments) land soil, respectively. The spatiotemporal versatilities of Hula Valley upper layers of the Peat soil properties are indicated by representative data of organic matter content in the Hula Peat soil: 43% (Barnea 2009); 65% - [5]; 30% - 54.9% [6]; 1945: 50% - 75%, 1970: 30% - 50%; 1985: 20% - 30% [7] [8].

Anthropogenic involvement affected P dynamics in the Hula Valley during the post drainage and came through two major actions: Fertilization and agricultural irrigation. Both were discussed in the results, and conclusive chapters. Regional climate conditions affected P loading through headwater discharges as the result of erosion, which were presented and discussed.

2. Study Site (Figure 1)

The Hula Project (HP) territory (**Figure 1**) is part of the entire Hula Valley, which constitutes part of the northern section of the Syrian-African Great Rift Valley. HP is bordered between 70-61 MASL altitudes and 33˚06'12" North and 35˚36'33" latitude coordinates.

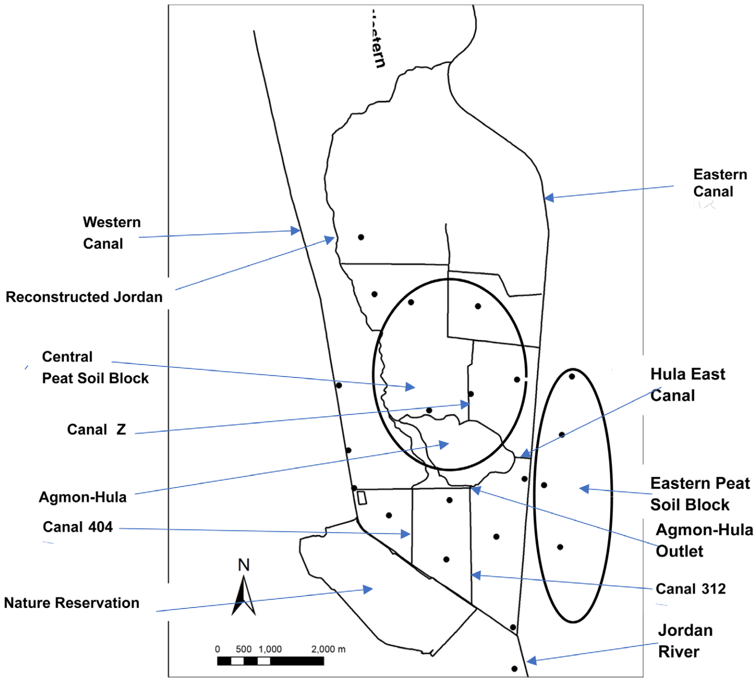

Figure 1. Chart map of the Hula Project territory: Inflow and drainage water lines and Peat soil blocks regions are outlined: Ecosystem compartments are arrowed; black dots are borehole drill locations for the underground water sampling.

3. Material and Methods

3.1. Sampling Methodology

Sampling Stations (**Figure 1**):

1) Underground (GWT) waters were sampled in the 14 boreholes.

2) The entrance of Canal Z into Lake Agmon-Hula (LAH). Canal Z conveys drained water from the Central block of Peat Soil.

3) The reconstructed Jordan entrance into Lake Agmon-Hula (LAH).

The final sampling program of location and frequency was a compromised optimization between budget availability and ecosystem-soil type constraints. The principles of the sampling program were restricted between two constraints: Actual presentation of the Hula Valley soil types and financial difficulties. Budget availability limitation enabled weekly or biweekly frequencies. The four stations imply the optimal (actually the minimal) number of stations, and the justification for this choice is given.

Unfortunately, information about soil moisture was not collected due to budget constraints. Therefore, the discussion about soil moisture and hydraulic conductivity is climatologically adjusted to wet, winter-spring and dry-summer-fall seasons.

3.2. Chemistry

The method for the analysis of Total Phosphorus (TP) and Total Dissolved Phosphorus (TDP) was Persulfate Oxidation/ascorbic acid [9]. Particulate P was calculated by subtraction of TDP from TP.

The data was obtained from the Hula Project Monitor Program (1994-2024): Migal-Galilee Scientific Research Institute, Jewish National Fund and Israel Water Authority.

3.3. Statistical Methods

Statistical evaluation included the following methods: Quadratic, and Linear Regressions (w/CI 95%) and scatter plot. Quadratic and Linear regressions (w/CI 95%) are used for modeling relationships between variable distribution with a parabolic best-fit curve, as most likely relevant to the analyses presented in this paper.

The statistical evaluation was carried out using the software STATA 17.0-Standard Edition for Statistics and Data Science. Soil features in the Hula Valley are highly variated and divided into three major groups: mineral lake sediments, Peat and transitions. Peat soil drained water samples (sampling Station No. 57) were collected from the outlet, which inflows into LAH. These samples are the optimal presentation of the porewater content of the central Peat soil block. The porewaters within the eastern Peat soil block (sampling station No. 73) are optimally presented in the outlet of its drainage canal, which inflows into LAH.

4. Results

Results given in **Figure 2** indicate a significant increase in TP concentration in Peat soil drained water (Station 57) during the summer-fall season. The total averaged TP concentration for the winter-spring (December-April) season during 1994-2019 (165 samples) was 0.093 ppm (SD 0.064) and for the summer-fall months (May-November) (208 samples)—0.111 ppm (SD 0.091), 20% elevation.

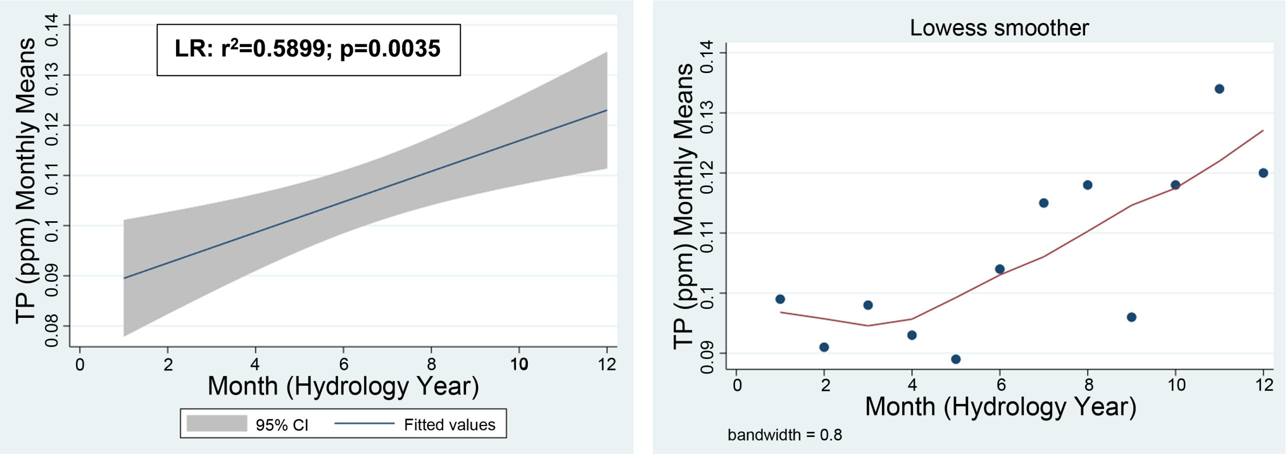

Figure 2. Seasonal distribution (left panel: Linear Regression; right panel: Lowess smoother) of monthly means of TP concentration (ppm) measured at station 57 during 1994-2019. The month numbers refer to Hydrological seasonality: From 1 = December (beginning of 1 - 4 winter rainfall season), to 12 = November next year (5 - 11 summer-fall seasons): left panel: Linear regression (r^2 and p values are given) with Confidence Limit (95%); right panel: Lowess smoother plot.

The results presented in **Figure 3** indicate an absence of distinct seasonal trend seasonality of TDP concentration changes in the Peat soil drained waters (Station 57). The distribution pattern of TP concentration was seasonally elevated (**Figure 2**) whereas that of TDP was not. Consequently, it is suggested that Peat soil dryness enhanced the breaking of large-size organic particles carried adhered P. Geochemical dissolving probably wasn't the dominant factor that enabled P to be released into the soil solution.

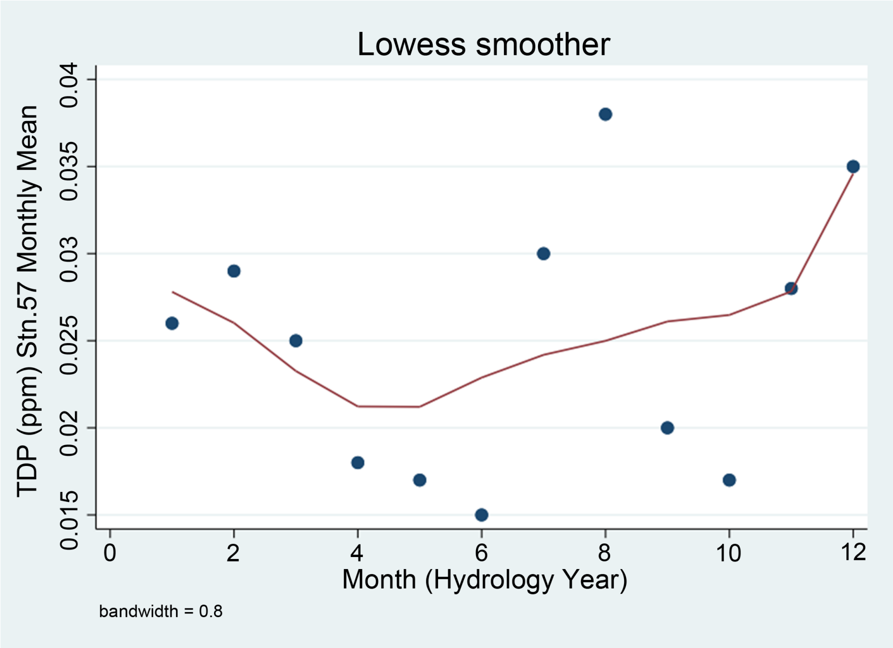

Figure 3. Lowess smoother plot of the Seasonal distribution of monthly means of TP concentration (ppm) measured at station 57 during 1994-2019. Months are numbered in a seasonal-hydrological order: From 1 December (beginning of rainfall season) to 12 November next year (summer-fall termination).

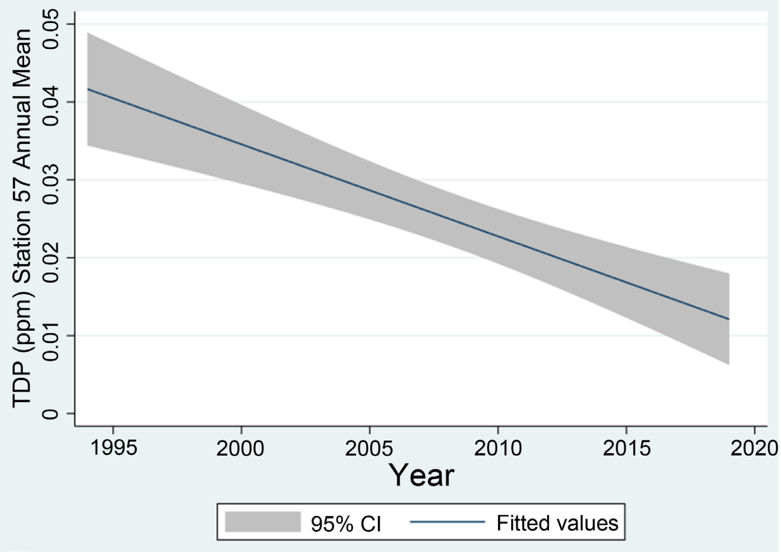

Figure 4. Linear Regression (w/CI 95%) of the temporal (1994-2019) changes of annual means of TDP concentration (ppm) in Peat soil drained waters (Station 57).

The experimental study of the Moisture Redox Concept (MRC) suggested that the increase of soil moisture is a factor that enhances Peat soil redox potential decline, resulting in dissolved P transfer from organic matter into a liquidized fraction. The HP implementation enhanced Peat soil moisture, but it was insufficient to significantly reduce TP migration. Nevertheless, the TDP decline was confirmed, probably resulted by summer water allocation ("Peat Convention"). It is suggested that temporal TDP decline (**Figure 4**) and TP enhancement (**Figure 5**) reflect both an insufficient wettability elevation. The role of agricultural fertilization was confirmed as having negligible impact on P content in the drained waters due to its high absorption capacity to soil particles [3].

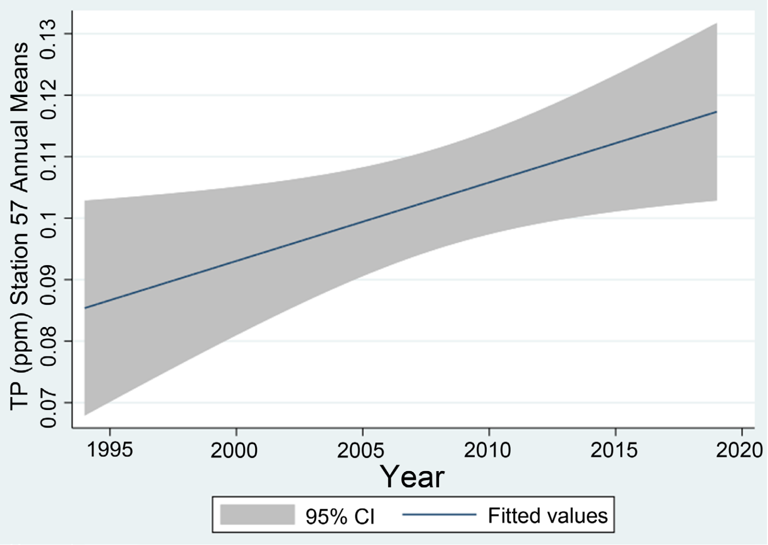

Figure 5. Linear Regression (w/CI 95%) of the temporal (1994-2019) changes of annual means of TP concentration (ppm) in Peat soil drained waters (Station 57).

The temporal distribution of rainfall capacity (**Figure 6**) indicates a fairly stable pattern during 1994-2024. Nevertheless, the temporal elevation of TP record in Station 57 (**Figure 7**) was probably resulted by an insufficient support of summer water (Peat Convection).

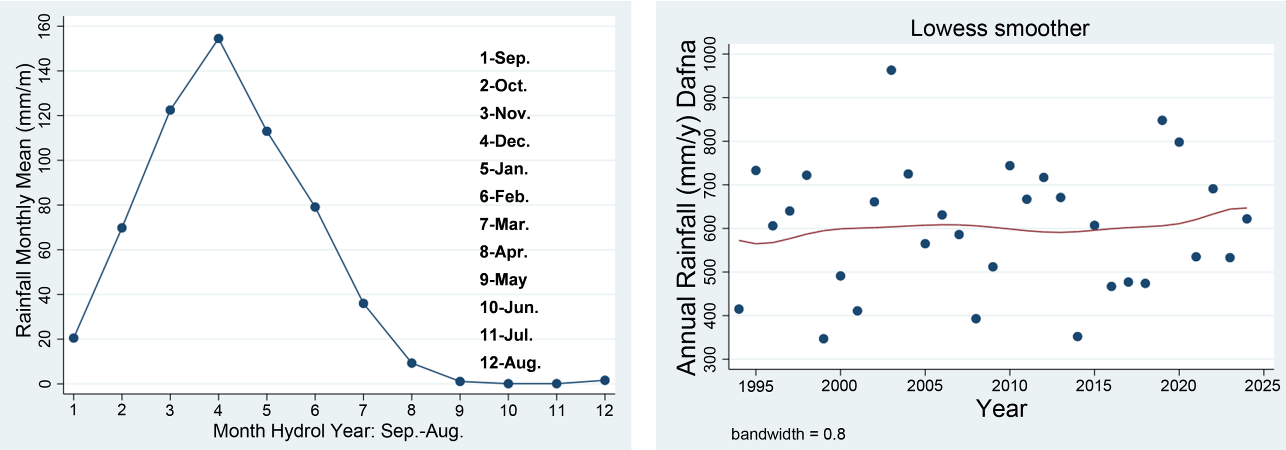

Figure 6. Annual (mm/y) and monthly (mm/m) rainfall record (Dafna) during 1994-2024. Left panel: Monthly (September-August) means scatter plot; Right Panel: Annual means as Lowess smoother plot.

Results given in **Figure 6**, on the right panel, indicate a fairly stable trend pattern of temporal fluctuations, whilst the subtropical climate of short rainy winter and long dry summer is shown in the seasonal presentation (left panel).

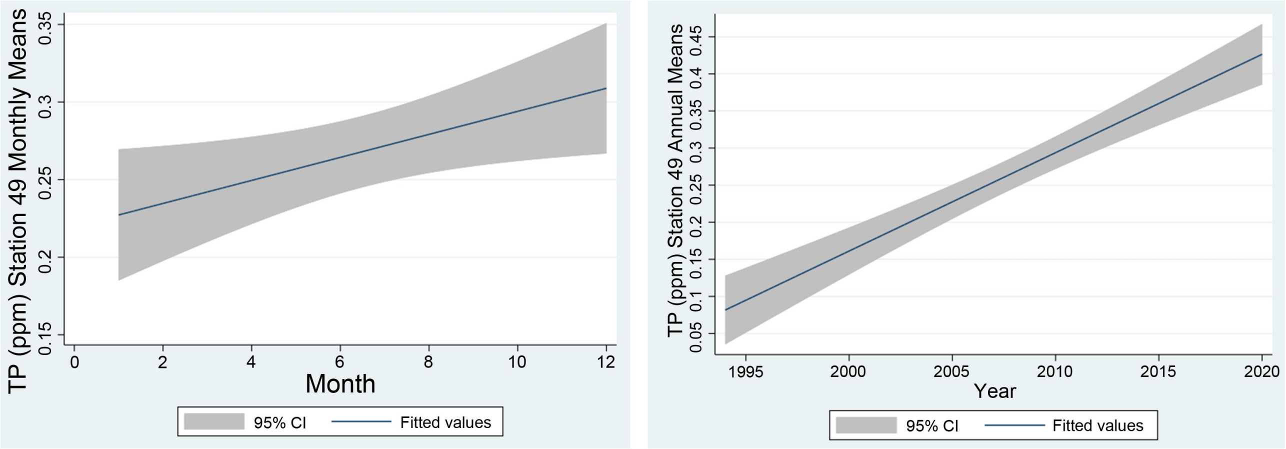

Figure 7. Linear regressions (w/Cl 95%) of Seasonal (left panel) and annual temporal (right panel) TP concentrations in the LAH effluent.

Results given in **Figure 6** confirm a distinct correlation between the hydromorphometric properties of LAH and seasonal changes in submerged vegetation growth biomass. Durng1994-2024, the volume, surface area and water depth in LAH were reduced: surface area from 1100 to 800 10^3 m^2, mean depth—from 60 to 20 cm and consequently volume from 0.7 to 0.2 10^6 m^3. The major source of P in LAH waters (as measured in the effluent) is the seasonal onset and decomposed offset submerged and emerged plants. The onset rate, intensity and timetable of the vegetation growth were not changed. The declined LAH water volume consequently enhanced the TP concentration in LAH waters. The seasonal plant tissue degradation released TP, which was incorporated by rooting plants from the sediments. LAH is, therefore, considered an offside ecosystem where P is assembled and released, apart from the issue of P dynamics in the Hula Peat soil.

The evaluation of the long-term record of TP and TDP concentrations in the Reconstructed Jordan River confirmed insignificant seasonal (monthly) and temporal (annual) correlation except for temporal TDP. The reconstructed Jordan current route branches out from the Jordan headwater at the northern tip of the Hula Project territory. Along its flow down into LAH and the western canal, the impact of the Peat soil is probably minor. Consequently, the P content as other nutrients was probably loaded outside the Hula Valley. Likely, the slight and significant reduction of TDP loading in late 2010th (**Figure 8**) was a result of changes in climate conditions.

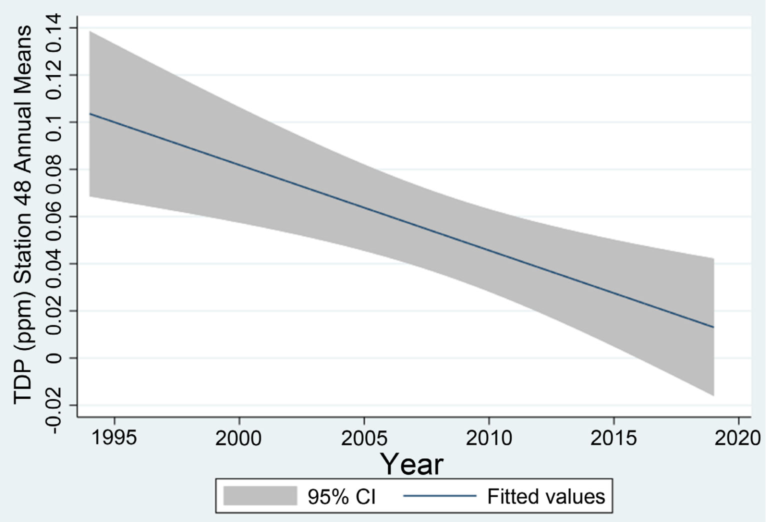

Figure 8. Linear regressions (w/CI 95%) of annual (1994-2024) temporal changes of TDP concentrations in the water of the reconstructed Jordan River (Station 48).

The results given in **Figure 9** indicate a similar property trend of TP migration: low during winter and increase in summer. However, the low level of significance is due to the impact of western freshwater intrusion through runoffs, seepage and/or other underground flows.

5. Discussion

Phosphorus is a well-known limiting factor of terrestrial and aquatic plant growth [10] [11] and about 30% of the global load of organic Carbon is stored in Peat [12]. The impact of Phosphorus on plant production and on the organic matter load in Peat is significant [13]. The Hula Peat soil drained water composition data presented in this paper include long-term (1994-2024) records sampled at four stations. Each of these sampling stations represents part of the Hula agricultural-touristic land use: Station 57 represents the central Peat soil block; Station 48 represents the composition of the reconstructed Jordan River waters of which a major part of the nutrient loads are sourced outside the Hula Valley territory; Station 49 represents the water quality in LAH; Station 73 represents drained waters assembled into "Hula East canal". The objective of this study is to explore the impact of climate conditions and anthropogenic involvement on Peat P loads and their migration into the soil solution and further locations. LAH and the Jordan waters ecosystems are therefore excluded, because of the dominant impact of non-attended factors. Conceptual ecosystem structures were attributed to the linkage between Phosphorus and Peat soil particles and consequently P migrative trait.

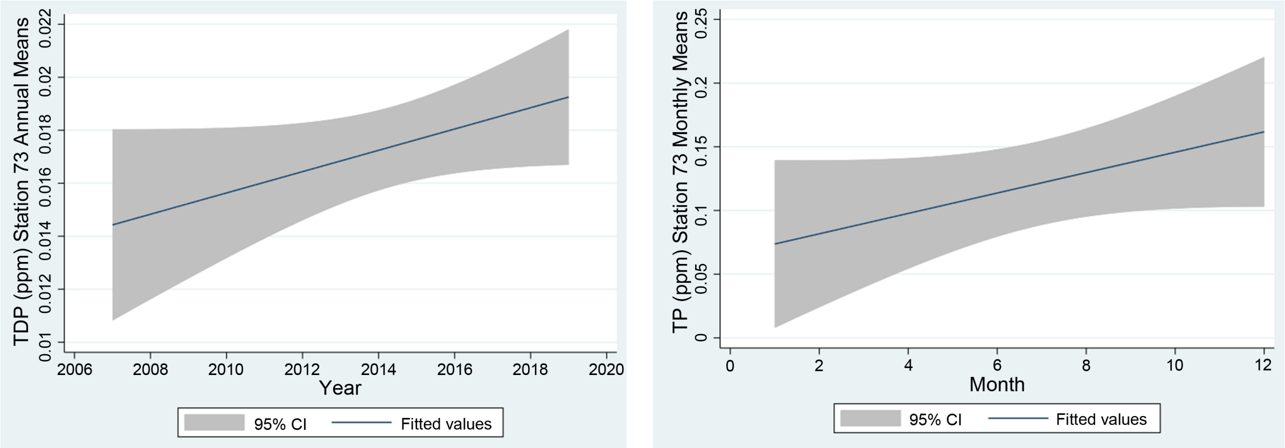

Figure 9. Linear regressions (w/CI 95%) of annual (1994-2024) (left panel) temporal and seasonal (monthly) changes of TP concentrations (right panel) in the water drainage from the eastern Peat soil block (Hula East, Station 73). The low significance level is indicated.

5.1. The Microbial-Enzymatic Concept (MEC)

The high content of organic matter and low pH levels characterize the high concentration of P in Peat soil [14] as well as its high bioavailability and relatively low fluctuability [15] [16]. Many studies attributed it to the strong adsorption force of P to organic matter and the low activity of Phosphatase enzymes [17]. Several types of rhizosphere bacteria enhance the excretion of phosphatases in the presence of plant root system biomass and consequently P bioavailability and probably migrated capabilities are well-known as common in Bog-Peat ecosystems [18]-[26]. It is noticeable that the decomposition of the plant root system in Peat ecosystems is a slow process [27]. The ecological key factor of P migration in such a case, as mostly concluded is due mostly to the substrate substances, of which the bioavailable portion is Orthophosphate (PO_4^{3-}). Free Orthophosphate is the only bioavailable P form that is most accessible for being assimilated by plants and bacteria [28]. The dissolution and desorption of both organic and inorganic P are highly sensitive to the changes in soil oxidative level, pH and Phosphatase enzymatic activity [29] [30].

5.2. The Geochemical-Moisture Redox Concept (MRC)

Peat soil in the Hula Valley is a principal compartment of the drainage land that was converted from a natural wetland and old shallow lake into agricultural land use. Soil properties within the land use in the Hula Valley are uneven. The northern-central part is organic Peat, and the southern part is mineral (marl soil). In between those regions, a "transition" soil section is located [1]-[4] (**Table 1**). The level of soil content of accessible P for plant uptake ("Olsen") in the north and south regions are close, whilst P bound to soil particles in the north is stronger due to the higher content of the organic component. A recent soil properties survey [4] has indicated a significant decline of organic content in the northern part, whilst it has increased in the south during 2018-2021. Most of the Peat Inorganic P (PI) exist as Ca-P complex minerals or adhere to Fe-oxides [3] [31]-[39]. However, the mineralization rate of organic-P (OP) is flexible and depends on several factors, such as soil aeration, moisture, and pH [40]. Moisture increases enhance oxygen depletion end reductive conditions accompanied by dissolution of Ca-P complex mineral as well as Fe—oxides resulting from P transfer into the porewaters (soil solution) [3] [35]-[39]. Redox potential and pH are dominant factors that enhance P concentration in the soil solution (pore water) [37]. An increase in wettability enhanced the destruction of organic matter, reductive conditions and dissolution of Fe oxides and hydroxides accompanied by adhered P release into the soil solution [3] [35]-[40].

5.3. Soil Moisture and Phosphorus Linkage Concept: (WDC)

P content and organic matter in the Peat soil are known to be highly correlated [14]-[16]. Adsorption of P onto organic matter particles exhibits a complex binding behavior, potentially involving geochemical redox-type reactions with other elements or by physicochemical interactions correlated with wettability range. Organic matter oxidation enhances the breakability of P adhesion onto the organic matter and its transfer into the porewater (soil solution) forwarding migration [41]. The rate of the oxidation of the organic matter is dependent on the soil moisture. The lower the moisture is, the oxidation is enhanced and adhered P transfer from soil particles into the porewater fraction is more intensive. Soil dryness enhances organic matter oxidation and P transfer into the porewater and migration capabilities. This P feature explains the summer increase of P concentrations in Peat-drained waters as documented and statistically evaluated in a long-term (1994-2029) record. The organic content in Peat and mineral soils during the fall months of 2018 and 2021 [4] has indicated a clear decline in Peat soil, which is probably correlated with adhered P reduction. This decline is probably due to the implementation of the "Peat Convection" of summer moisture enhancement. The pattern of seasonal and temporal distribution of TDP concentrations in the drained waters was not accompanied by significant fluctuations, whilst TP, as given in this paper, fluctuated significantly. It is likely that dryness facilitated the breakdown of large-size organic particles into smaller fragments, retaining P that is subsequently analyzed as the fraction of TP while being excluded from TDP.

Therefore, the conclusion is that the enhancement of dryness accompanied by wettability and reduction of TP migration is likely. The P-content of Peat soil is correlated with organic matter capacity. The primary link type between organic matter and P is through adsorption. However, when the organic matter undergoes oxidation destruction, this bond is disrupted. Higher moisture levels result in lower destruction of organic matter and the transfer of unbreakable P-links into the soil solution. The distribution of TP, TDP and Particulate P (Part. P) (Particulate P) in Peat soil was intensively discussed [42]. The complex interaction between those three P fractions and the resulting P migration through the drained waters and, consequently environmental implications was studied [43]. Different TP and TDP rates of load reduction were documented as a result of P load reduction. Though the geochemical mechanism of migrated P contribution from Peat soil into the environment is complicated, seasonal overlap probably does not exist. An Independent seasonal summer dryness P migration trait in the Hula Valley is likely and might be slower by wettability enhancement through summer irrigation allocation. The redox model controls the winter P migration, and the dryness model is dominant in summer-fall. The peat soil dryness model suggests that the enhancement of P migration is due partly to the breakability of P bounds to organic particles. The geochemical model correlated wettability anoxia and redox, resulting in migrated P migration, whilst the dryness model correlated it with particulate P breakability. The impact of the redox conceptual model during summer is likely to be negligible but dominant in winter. As confirmed by the data record, the dryness model is dominant in summer. The long-term (1994-2024) monthly record of TP, TDP and Part. P concentrations (ppm) are shown in **Table 2**.

Table 2. Monthly means (1994-2024) of TP, TDP and Part. P concentrations (ppm) were measured in Station 57 (central peat block drainage).

Month	TP (ppm)	TDP (ppm)	Part. P (ppm)
1	0.126	0.042	0.084
2	0.098	0.033	0.065
3	0.099	0.028	0.071
4	0.086	0.019	0.067
5	0.093	0.019	0.074
6	0.102	0.029	0.073
7	0.112	0.057	0.055
8	0.11	0.024	0.086
9	0.098	0.017	0.081
10	0.12	0.027	0.093
11	0.119	0.036	0.083
12	0.102	0.027	0.075

Statistical evaluation of the data given in **Table 2** confirmed the inverse relation between TDP and Part. P concentrations, and months. On the other hand, directly proportional relationships between TDP, and TP concentrations and months (*i.e.*, summer decline) were confirmed. The peat soil summer ecosystem is consequently characterized by a decline in TDP, whilst Part. P elevation initiates TP enhancement. These properties are changed by moisture elevation.

5.4. Agricultural P Fertilization Concept (AFC)

The potential impact of agricultural P-fertilization on P mobilization from cultivated land into drainage canals forwarding further into Lake Kinneret was intensively studied [3] [35]-[39]. Experimental investigations about the P-transfer mechanism based on Lysimeters trials were mostly linked to the MRC model. Final summarized conclusions [3] formulated a negligible transfer of 0.9 mgP/m^2/day into shallow-depth groundwater from fertilized tomato crops on lime soil for 110 days. Nevertheless, the P adhesion capacity of peat soil is much higher (900 - 1400 mgP/Kg soil) [44]. Consequently, P leakage from Peat soil into the underground during the long-term management of surplus P fertilization capacity is not predicted [3]. Meanwhile, in lime soil, as commonly distributed in southern Hula Valley, it is possible, but experimental Lysimeters research was confirmed as negligible. Moreover, the very low rate of Hydrological Conductivity of Peat soil minimized fertilized P migration to an even lower measure. Most of the surplus fertilized P that was not incorporated by plant crops remains adhered to the Peat soil organic particles and has not migrated into the underground waters [3]. Quantitative information about P fertilization is available, and the high absorption capacity of P by Peat soil was mentioned and discussed. Consequently, P fertilization has no significant impact on P migration in Peat soil. Selected correlations between migrated P and one of the four presented concepts reject the hypothesis of fertilized P contribution (AFC).

6. Conclusive Remarks

The evaluation of the P migration from the Hula Peat Soil discriminates between internal and external features. Therefore, sampling sites are crucial for a comprehensive conclusion. The outflow of Canal Z into LAH was selected as the optimal presentation of the Peat soil contribution in the Hula Valley. Peat-originated P was also analyzed in water samples from other stations, 58, 49, 73 and canals “Zero”, 404 and 312. P sources in those stations were lime soil composition type, raw sewage leakage, and sub-submerged vegetation biomass in LAH. Evidently, 20 years averaged annual total TP outflow from LAH is 1.347 t/y whilst annual TP input through Canal Z (Station 57) into LAH is 0.573 t/y. Consequently, in addition to the Peat soil TP contribution of 0.774 t/y by LAH, this is due mostly to submerged vegetation. The ecological-edaphic conditions that enhance P migration through water mass motion, plant uptake mechanisms or microbial-enzymatic processes, including geochemical and moisture traits, are widely known. If P concentration increases as the result of soil moisture and anoxic enhancement, resulting in reductive conditions [3] [35]-[39], why long term records and monitor reports documentation indicate summer higher and winter lower P concentrations in Peat drained waters (**Figure 5**) [45]-[48]. A long-term trend of organic matter capacity in the Peat soil was clearly confirmed [3]. Consequently, summer moisture enhancement (Peat convection) probably diminished the destruction of organic matter and the decline of P migration. The MRC model predicts P migration enhancement under moisture enhancement, which is in controversial status with WDC. The MRC considers enhanced P concentration resulting from increased wettability, whilst the WDC predicts the opposite, reduced P concentration. Long-term data evaluation recommended summer wettability (irrigation) enhancement of Peat soil land aimed at reducing P release into the drain and forwarding the diminishment of P input into Lake Kinneret. According to the MRC model, additional summer wettability might enhance P contribution from the Hula Peat soil to Lake Kineret, which is practically undesirable management, whilst the WDC model predicts the opposite. The evaluation of long-term records of nutrient distributions within the drained waters in the Hula Valley confirmed low P concentrations during winter-spring months and higher in the summer-fall season, whilst MRC predicted the opposite pattern. Peat soil wettability management as supported by the "Peat Convection" will slow down the rate of organic matter destruction in Peat soil followed by reduction of P migration. The characteristics were confirmed and documented in the HP annual reports, which show that total phosphorus (TP) concentrations in Peat drained waters (Station 57) are high [49] during summer. Environmental conditions in the Hula Valley are different and therefore the implication of the MEC model is inappropriate as supportive tools for management design. The regional subtropical climate trait and the agricultural management design disqualify adjustment of the MRC model. The long-term data record revealed a contradiction between the MRC and WDC conclusions. As for the MRC in summer, P migration was predicted to decline but field data and the WDC conceptual background confirm the opposite, P migration enhancement. The role of the AFC model requires practical improvement. Conclusively, the utilization of the WDC model is recommended. The principle conclusion for future management is therefore additional allocated summer water irrigation aimed at reduction of P leaking into Lake Kinneret.

Acknowledgements

Sincere appreciation is given to Prof. D. Levanon and D. Klein, for fruitful and friendly collaboration; to V. Orlov-Levin and M. Peres, for unpublished data supply and T. Natanson, and E. Yasur for field sampling assistance.

Author Contributions

The author carried out data analysis, evaluation and the preparation of the original draft and final version.

Data Availability Statement

The data presented in this study are available on request from the corresponding author.

Funding

This study was supported by the Migal-Galilee Scientific Research Institute.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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