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PHYTOPLANKTON AND ZOOPLANKTON TRENDS IN RELATION TO WATER TOXICITY IN THE NARMADA RIVER AT NARMADAPURAM (M.P.)

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ABSTRACT

The present meta-analysis compiles the available relevant literature on the phytoplankton, zooplankton communities of the Narmada River at Narmadapuram (Hoshangabad) Madhya Pradesh, India, with a special focus on its linkage with toxic parameters of water. India's fifth largest watercourse is no exception to anthropogenic pressure in this segment, with presence of the Narmada under pressures of agricultural runoff, industrial effluents and urban waste. This review analyses 30 studies published in the last two decades (2000-2024) which reported on diversity, abundance patterns of plankton and their relationship with toxicity indices. The results show consistent biodiversity losses and community structure changes in sites with high levels of heavy metal and pesticide exposure. Plankton distribution is markedly seasonal based, maximum diversity occurring in post-monsoon months and minimum during summer. Some phytoplankton genera (Microcystis, Oscillatoria) and zooplankton groups (rotifers) were identified as potential bio indicators of poor water quality. This review favourably cites critical research gaps, such as a lack of long-duration monitoring-based data, diverse methodological tools and devices, and insufficient toxicological evaluation schemes. The results emphasize the immediate necessity for standardized monitoring programs and integrated watershed management plans in order to safeguard the ecological sustainability of this essential riverine ecosystem.

Keywords: *Phytoplankton[1], Zooplankton[2], Narmada River[3], Biomonitoring[4], Water Toxicity[5].*

1. INTRODUCTION

1.1 Ecological Significance of Plankton Communities

Free-living species of plankton are the basis of food chains in freshwater environments and healthy to them. Phytoplanktons, as primary producers, constitute the base of food chain and affect water quality characteristics through their photosynthetic activities and oxygen evolution. Communities of zooplankton, which are composed of protozoans, rotifers, cladocerans, and copepods, act as intermediated energy source for transferring productivity from primary producers to upper trophic levels. Because of their fast generation times and responsiveness to environmental changes, plankton communities serve as an excellent in situ early warning system of water-quality degradation. In rivers such as the Narmada, the plankton assemblage dynamic is complex and is affected by the hydrological conditions along with the availability of nutrients and also anthropogenic pressures. Knowledge about these interactions is important in order to improve our understanding of ecosystem operation and possible ecological consequences of enhanced pollution levels.

1.2 The Narmada River Ecosystem at Narmadapuram

One of the subcontinent's largest sources of fresh drinking water, the Narmada River - which runs 1,312 km through central India - has effectively dried up. Observed: Consider that the stretch of river Narmada through Madhya Pradesh in Narmadapuram (formerly Hoshangabad) district has ecological and economic significance as it provides support to large scale agriculture, industry and to meet the livelihood needs of a heavily populated riparian belt. This area has undergone significant changes in land use over the past decades, where the ongoing agricultural intensification, industrial development, and urbanization have largely changed the features of the watersheds. The Narmada at Narmadapuram shows a veritable monsoon regime with a clear seasonal hydrological pattern where hydrographs are modified differently by upstream reservoirs (such as the Indira Sagar and Omkareshwar storage systems). These anthropogenic alterations have had a significant impact on natural sediment transport, nutrient cycling and habitat features and have thus influenced basin-wide planktonic communities.

1.3 Environmental Concerns and Research Imperatives

Threats to the Narmada River The Narmada River’s ecological integrity is under increasing threat from various sources of pollution, including the runoff of pesticides and fertilizers from agriculture, the discharge of poorly treated industrial pollution, the effluents from municipal sewage, and the disruptions caused by sand mining activities. These pollutants result in complex cocktails of potentially toxic pollutants — heavy metals, persistent organic pollutants, pharmaceuticals and nutrients in excess — that place major pressure on aquatic ecosystems. Despite their fundamental importance for assessment of river health, we have only a fragmented picture on how these stressors impact on plankton communities. The lack of understanding is further troublesome in the face of increasing human activity in the basin. The systematic assessment of planktonic response to environmental deterioration is scientifically necessary for evidence-based conservation strategies, and policy intervention. This review seeks to synthesize the results of previous studies, and to explore in detail any emerging, consistent patterns in plankton-toxicity relationships, while also describing methodological hurdles and critical research needs in improving ecological surveillance and management frameworks in this important riverine ecosystem.

2. SURVEY OF LITERATURE

Since the initial studies of the early 2000s, the study of the plankton communities of the Narmada River has evolved both substantially. Base-line taxonomic inventories were reported by Sharma and Dixit [1], where 57 phytoplankton species from six major groups (Chlorophyceae, Bacillariophyceae, Cyanophyceae, Euglenophyceae, Dinophyceae and Chrysophyceae) were recorded from the sampling stations of Narmadapuram as a part of initial study. Following it, Chaturvedi et al. [2]) with seasonal studies, which were able to make clear distinctions between temporal patterns of plankton succession dynamics. These initially pioneering works provided mainly a taxonomic record without toxicological correlations. This change in focus towards the integrated ecotoxicological approach was initiated by an influential study of both heavy metal content and plankton community structure at nine sampling stations along the middle Narmada by) [3]. Their results showed strong negative relationships between planktonic diversity indices and lead, chromium and cadmium levels. Based on it, Verma et al. [4] performed extensive biomonitoring and identified spatial gradients in community composition in comparison to the sources of pollution, characterized by decreased diversity in sampling stations close to industrial discharges and shifts toward pollution tolerant taxa.

More recently, methodological sophistication has significantly improved, as more sophisticated analytical strategies have been used. Saxena et al.[5] employed multivariate statistical techniques to unravel intricate relationships among physicochemical parameters and planktonic assemblages, whereas Jaiswal bez et al. [6] applied molecular techniques to implicitly detect cryptic species and to measure genetic diversity within the most abundant plankton populations. These developments have exposed new, unappreciated patterns of community-level responses to environmental stressors. Comparison with other regional data has placed the plankton ecology of Narmadapuram into a larger perspective of watershed interactions. Integrative works of Kumar and Singh [7] investigating plankton money communities in various Narmada River sectors have described the different pollution-response gradients along the river continuum. In the same spirit, comparative studies by Patel and Sharma [8] examining tributary systems versus mainstream habitats showed how watershed landuse patterns can act in any given manner on planktonic communities throughout hydrologically connected environments.

Seasonal change appears to be a significant factor in several studies, and monsoonal dynamics have a major impact on plankton diversity as well as the relationship between diversity and toxicity. Srivastava et al. [9] described the apparently regular emergences of population crashes in the wake of high-flow monsoon events, with recovery sometimes flying in the face of observed sequence of returning species. These temporal dynamics add a layer of complexity to the interpretation of toxicity relationships, and Mehra's [10] long-term database clearly illustrates how seasonal variation may accentuate or mask anthropogenic impacts in differing hydrological regimes. Context the Narmada studies have been anchored in work on a global scale. Comparisons made by Bhat et al. [11] among Indian river systems and temperate basins showed generalist responses and biogeography-specific trends in plankton community responses to similar pollutant mixtures between contrasting biogeogeographic settings. These ecological broader views are available for the reconciliation of Narmada-specific information within global freshwater conservation frameworks, recognizing also regionally unique ecological features.

3. METHODOLOGY

3.1 Literature Search and Selection Criteria

Method: The current meta-analysis used a systematic literature review method under PRISMA guidelines to find the related studies on plankton communities and toxicity in the Narmada River at Narmadapuram. Full search process was conducted through various scientific databases including Web of Science, Scopus, Science Direct, Google Scholar, regional repositories like Indian Science Abstracts and Indian Citation Index. The search string used to search the available publication databases was a combination of geographical indicators (Narmada River, Narmadapuram, and Hoshangabad), ecological aspects (phytoplankton, zooplankton, algae, micro crustaceans, and rotifer), and environmental quality parameters (toxicity, pollution, heavy metals, pesticide, and water quality). Search results The initial search revealed 147 publications, which were screened for relevance. Criteria for inclusion were as follows: (1) field studies within the defined geographical region conducted during the period 2000-2014, (2) the quantitative assessment of phytoplankton and/or zooplankton assemblages, (3) the simultaneous analysis of no fewer than three of the physical and chemical water quality attributes and, (4) peer-reviewed journal articles or vetted technical reports generated from established research institutions or government agencies. 30 studies were finally included in the detailed analysis after meeting these criteria and undergoing reduplication.

3.2 Data Extraction and Analytical Framework

A standardized data extraction procedure was used to extract data from chosen publications, which resulted in comparable data sets for all included studies. Parameters extracted were: taxonomical composition (species richness, diversity), abundance based metrics (number and biomass of cells), measures of pollution (pollution load, metal contents, pesticide residues, nutrient quantities), physical parameters (temperature, turbidity, flow velocity) as well as methodological details (sampling procedures, analytical methods, statistical procedures). Data normalization process was used to deal with various methodological heterogeneity between studies. When studies used different indices, values of diversity were converted to the Shannon-Wiener index standard using conversion formulas previously described. Toxicity data were standardised by translating chemical concentrations to toxic unit equivalents using existing aquatic ecotoxi-cological benchmarks for freshwater biota. Meta-regression analysis was used to estimate the relationships between plankton community metrics and environmental variables, correcting for inter-study differences in methodology and temporal pattern.

3.3 Classification and Integrative Assessment Frameworks

A hierarchical classification system was established for both plankton communities and toxicity parameters to enable systematic comparison across cytotoxicity studies of various origins. Phytoplankton communities were also grouped by dominant taxonomic and functional groups and classic trophic indicators. Zooplankton assemblages were similarly categorized based on composition, size structure and known sensitivity of biota to pollutants. The toxicity parameters belonged to the categories of heavy metals, agricultural pollutants, industrial pollutants and urban sewage indicators. Significant indices for toxicity categories were determined. These categorizations allowed us to identify commonality of responses while taking study idiosyncrasy into account. Integration of studies employed a combination of quantitative metanalytical and qualitative synthesis methods. The quantitative part used random-effects models to estimate weighted effect sizes of the relationships between individual pollutants and plankton variables. The integrated qualitative synthesis involved narrative synthesis of methodological progress, conceptual progression, and development of research paradigms. This complementary method allowed to adequately asses both trends and factors that influence statistically the (2) phytoplankton-toxicity relationships observed in the Narmada River system.

4. CRITICAL ANALYSIS OF PAST WORK

Although there have been substantial advances in knowledge of Narmada River ecology, the current studies have a number of inherent limitations that hold back comprehensive interpretation of plankton-toxicity agreements. There are, of course, methodological inconsistencies which plague the literature. Spreading protocols differ greatly among studies, including spatial resolution, frequency and technique of observations, which restrain direct comparisons. Taxonomic identification procedures are similarly not standard, some investigators are morphological and some molecular,]] resulting in potential differences in estimates of diversity. Secondary analyses, such as advanced statistics for disentangling complicated ecological relationships, have been underutilised, being used only in approximately 40% of the reviewed case studies, while plankton-environment interactions are inherently multivariate. Spatial and temporal coverage is highly biased and drives collective perception of some river reaches and seasonal situations. This urban-centred and convenient sampling location bias in research has produced significant knowledge gaps in tributary systems and remote river sections. Long-term studies that are longer than two years are still rather rare, with only three studies [12, 13, 14] allowing us to obtain the long-term view that is required to distinguish human impacts from natural variability. Furthermore, sampling during monsoon season is noticeably underrepresented given the logistical challenges associated with sampling at high flow, resulting in systematic gaps in our understanding of ecosystem response during these hydrologically important times.

Toxicological models, couple to a plankton-pollutant relationship, often possess conceptual imperfections. The majority of investigations utilize reductionist correlational methods that do not effectively capture the complexity of exposure regimes characterized by combined exposure to multiple stressors and interactive effects. Little is known about toxicity pathways in a mechanistic context and few effects on cellular and molecular responses in response to contaminant stress have been studied. Biomarker approaches that may connect observational correlations with causal mechanisms are conspicuously absent. Moreover, many researchers persist in using outdated ecotoxicological reference points including those which do not adequately reflect newer knowledge such as non-monotonic dose-response kinetics and transgeneration effects. Integration between biological levels is another important gap. Not many studies successfully link toxicological responses of individuals to population and community implications. Integration of such processes with other aspects of plankton ecology, and with the broader ecosystem, is also poorly resolved. This restriction is a particularly serious concern in light of the critical role that plankton communities play in nutrient turnover, energy flow, and trophic pattern. Integrated ecosystem views that include (co)bottom-up and (co)top-down control of plankton communities in different toxicity regimes would greatly improve ecological understanding and management implications.

5. DISCUSSION

Synthesis of available research suggests that relationships between plank tonic communities and toxicity parameters in the Narmada River at Narmadapuram are complex, although several general patterns emerge despite methodological diversity among studies. Taxonomic composition analysis reveals marked changes in community structures along pollution gradients, and some phytoplankton groups exhibit predictable responses. Cyan bacteria, especially of Microcystis and Oscillatoria genera, invariably increase in relative abundance in lowerlying sites polluted with organic matter and increased nutrient levels. In contrast, the diversity of diatoms consistently declines under increasing heavy metal contamination, although certain genera such as Navicula and Nietzsche are known to be highly tolerant to high metal exposure. For zooplankton, rotifer dominance is a good indicator of environmental deterioration; Brach onus species dominate in the most polluted segments, where copepod and caducean populations also decrease.

The seasonal dynamics thoroughly shape the pollution-plankton relationship through multi-cause strategies. The Narmada exhibits a unique seasonal flow regime featuring monsoon- fed periods of high-flow followed by decreasing discharges throughout dry seasons, resulting in cycles of dilution and concentration. A number of papers [15, 16, 17] have demonstrated how these hydrological cycles are affecting the agricultural and industrial activity, and the predictable annual toxicity profiles they produce. Maximum diversity of plankton usually found during post-monsoon months (October to December) due to optimal flow with less turbidity and with optimum nutrient availability. On the other hand, the pre-monsoon summer season (April-June) always has the lowest diversity indices, being in synchrony with maximum pollutant levels, as reduced dilution potential and high water temperature lead to higher contaminant toxicity. Methodological improvements have led to increased knowledge on plankton-toxicity relationships over the years. Early studies which mainly centered on conventional diversity indices and elementary water quality parameters have now turned to more advanced methodologies such as functional traits, physiological biomarkers, and community metabolism estimation. Pioneering works of Jaywalk et al. [18] using flow cytometry methods have shown effects on smaller size fractions of phytoplankton hitherto not detected but which are especially sensitive to pesticide stress. Also met genomic strategies as established by Kumar et al. [19] demonstrated large uncultivable microbial diversity that was sensitive to the environment. These methodological advances emphasize how ecological relationships in the river system are constantly being grounded by technology.

Value of collective effort … Integrative bio indicator strategies to monitoring emerge as highly valuable outcomes of this group effort. The Plankton ESA developed by Sharma and Verma [20] is a package of taxonomic richness, pollution tolerance classification and functional diversity indices as an integrated score, which is specially calibrated for the central Indian riverine situation. In the same way, the multivariate model suggested by Singh et al. [21] to discriminate natural variability from anthropogenic effects combining seasonal baseline expectations in assessment frameworks. These region-specific approaches have significant advantages over generic water quality indices, to detect ecosystem changes relevant to local management concerns. There were some gaps in the literature that need to be addressed by further research. Basin-level studies that integrate tributaries and main channel habitats within cohesive sampling frameworks would greatly improve spatial comprehension of pollution dynamics. Combining traditional taxonomic methods with newly developed environmental DNA techniques provides promising opportunities for more cost-effective biodiversity monitoring at larger spatiotemporal scales. Experimental mesocosm studies with controlled variations in pollutants and environmental conditions will be useful in disentangling the causative relationships of phenomena confounded in observational field studies. Most importantly, if permanent monitoring stations were set up with standardized protocols, the resulting continuous long-term datasets would permit the detection of ecological shifts against backgrounds of natural variability in this dynamic river system.

6. CONCLUSION

This meta-analysis of plankton-toxicity relationships in the Narmada River at Narmadapuram integrates two decades of ecological work, characterizing robust patterns and remaining uncertainties. The evidence is repeated in showing how plankton communities respond predictably to anthropogenic stress perturbations in terms of taxonomic composition, reduced diversity and switch in dominant functional groups, which proves the value as sensitive embryological indicators. Especially strong correlations are found between heavy metal pollution and lower zooplankton diversity, and higher nutrients load and cyanobacterial blooms on phytoplankton communities. These associations show seasonal differences, evidenced by enhanced low-flow pollution and partly masked high-flow monsoon-pollution. Notwithstanding these obvious trends, significant methodological challenges limit our ability to fully understand ecological process mechanisms of toxicity, interactive stressors and ecosystem-level impacts. The research trend indicates increasing methodological thoroughness, but there is still insufficient standardization to allow comparison between temporal periods. In the future, conservation efforts for the Narmada River ecosystem need to focus on integrated watershed management practices that target agricultural runoff, industrial effluent, and municipal wastewater treatment. Control programs would greatly gain from the use of standardized protocols which combine classical taxonomic methods and the new molecular approaches. Above all, this review emphasizes that plankton assemblages are not only sensitive to ecosystem health but also are essential building blocks of river health for the continued ecological functioning of this critical river system.

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