Aquatic Ecosystems and Environmental Frontiers, Volume 4, Issue 3, September 2026 *ISSN: 3049-186X*
DOI: https://doi.org/10.70102/AEEF/V4I3/AF260317

Hydrological Variability and its Influence on Reproductive Synchronization in Freshwater Fish

[1*] Hafiz Rahman, Nusantara Skills and Leadership Centre, Cyberjaya, Malaysia.

[2] Siti Nurul, Nusantara Skills and Leadership Centre, Cyberjaya, Malaysia.

Abstract: Hydrological variability may influence reproductive spawning cues and habitat availability, but concentrated spawning and the correct timing of environment are separate ecological phenomena. This paper provides an evidential basis to the development of an analytical framework to differentiate between these ecological phenomena using two complementary metrics. Twelve scientific papers on recent research are the biological basis for the use of a transparent scenario analysis. Normal distributions with defined mean spawning dates and temporal standard deviations represent spawning dates, while the center of the hypothetical window of opportunity of habitat is constant. There are four synthetic scenarios of aligned spawning, delayed spawning, dispersed spawning, and delayed and dispersed spawning. The evaluated metrics are percentage of spawning happening during a period of fourteen days around population mean spawning date and the absolute difference between mean spawning date and habitat opportunity date. An increase in temporal standard deviation from 7 to 18 days decreases spawning concentration from 68.27% to 30.26%, while an increase in mean date by 21 days increases mismatch from 0 to 21 days without altering spawning concentration. These findings are consistent with both low concentrations and mismatch within the same setting. This is consistent with the specified assumptions made within the given framework. This approach explains the importance of distinguishing between temporal aggregation and environmental synchrony in terms of reproductive monitoring. It is important to have species-specific data, as well as habitat-specific data, along with flow manipulations, before using this framework.

Keywords: Freshwater Fish; Hydrological Variability; Reproductive Synchronization; Spawning Phenology; Environmental Flows; Timing Mismatch.

(Submitted: May 26, 2026; Revised: July 07, 2026; Accepted: August 25, 2026; Published: September 30, 2026)

I. Introduction

The phenomenon of reproductive timing serves as a good link between the changes occurring in the freshwater environment and the process of population rejuvenation. Either it can maintain its brevity but be detached from the favorable period of nursery growth or remain seasonally synchronized but distributed within the population. Both cases should be measured separately. There is evidence of long-term effects of the modified timing of low water and high-water periods on the state of reproductive systems in Amazonian floodplain fishes (Röpke et al., 2022). This work aims at solving the problem of measurement by applying the concept of reproducible timing.

Hydrological Context and Research Objectives

Hydrological variability includes timing, duration, magnitude, frequency, and rate of change. Seasonal average discharge cannot account for all these variables. In the case of the Yangtze River, the study of rising water spawning processes indicates that different elements of the hydrograph can vary differently. Thus, there is justification for studying the time structure of flows, rather than annual water volume, as an adequate description of reproduction conditions (Yu et al., 2023).

Reproductive synchrony is defined here as the clustering of spawning dates within a species. Environmental synchrony is defined separately as the closeness of the average date of spawning to the certain opportunity for habitation date. Thus, simultaneous spawning is not necessarily interpreted as favorable. The narrow spawning period can take place before the opportunity for nursery areas arises. On the other hand, the wide spawning period can overlap the suitable conditions only partly. Results from regulated river observations reveal that discharge, discharge variability, and water temperature can vary in

their correlation with the presence and abundance of larvae for different species of fish. Therefore, one response rule is probably not sufficient to cover all types of reproductive behavior. The mathematical model presented here does not include a discharge threshold or temperature threshold for all freshwater fishes (Griffen & Weber, 2025). This study aims to categorize current knowledge on the role of hydrological timing in relation to reproduction; define concentration and mismatch indices; and assess the influence of mean displacement and variability in time on these indices under certain assumptions. Contributions of this paper are in providing a measurement approach and a numerical example.

II. Literature Review

Reproductive Responses Vary Among Species

The latest research on the striped gourami in the Gomti River links reproduction phenology to local climate and hydrological characteristics and indicates a reproductive peak during July. The study of a wetland species Macrognathus pancalus finds a larger spawning period of May to August with June and July peaks. The differing seasonal descriptions justify assessing both the central tendency and variability without presupposing that either of the populations fits the distribution used in the current demonstration (Bano et al., 2025; Rahman et al., 2024). The research on Rita rita in the Burhi Gandak River is also situated within the monsoon period. Although such information provides a seasonal background for the area, the peak value of the gonadosomatic index does not provide the distribution of the actual dates of egg laying. It is necessary to differentiate between reproductive readiness and spawning for building the synchronization measure (Bezbaruah et al., 2025).

Flow Events Migration and Spawning Evidence

The study of fishery systems through the flood pulse framework indicates that the temporal patterns of hydrological anomalies are important in fish migration traits. Migration is responsible for obtaining reproductive habitat but does not necessarily imply spawning. Hence, migration peaks are meant to be used in the reproductive analysis as supporting evidence or as possible explanatory variables and not as a replacement for spawning records (Deng et al., 2023). Long-term monitoring of fishways in the Murray River further indicates that there is variability in flow and life history, and this does not mean that there will always be a consistent directional shift between fish populations. The current scenarios take into consideration only the timing aspect without expecting a climate change effect on fish reproduction schedules (Stuart et al., 2026). Species identification poses yet another challenge in the reproductive monitoring. Studies using quantitative metabarcoding have identified varying spawning cycles within Amazonian fishes. Pooling up larvae from different species may bring together larvae from different reproductive cycles thus giving a broader season when this is not actually the case. Therefore, metrics are supposed to be calculated per population or per species before making a conclusion on the whole assembly (Mariac et al., 2022).

Hydraulic Suitability and Environmental Flow Design

Estimation of grass carp drift model in the Maumee River takes into account the combined factors of flows, temperature, and spawning location in order to estimate the hatching and retention of eggs. This is an example of how an appropriate spawning date does not reflect the survival afterwards. The hydrodynamic transport and development conditions can be still limiting even after a successful cue detection and egg release (LeRoy et al., 2024). Pulse flow concept in the Second Songhua River incorporates such parameters as peak flow, timing, duration, and frequency. Species are also classified based on thermal requirements (Lv et al., 2023). This gives us an idea of the practical applicability of the present approach: a release schedule can affect the distribution of reproductive events, but at the same time, its ecological significance is determined by habitat conditions during the development process. Research on flood pulse variability and catch-effort dynamics in the Ganga River shows that it is difficult to interpret

fishery yields as reproductive output. Catch is affected not only by ecological factors, but also by the fishing effort and accessibility (Kelkar et al., 2022).

Research Gap and Analytical Scope

In this respect, the examined studies measure the various processes at different time scales. It is impossible to combine their outcomes into the effect of synchronization without similar measurements on the individual time scale. Methodologically, what we need is a clear distinction between reproductive concentration and environmental synchronization. A simple thought experiment may show how these measures work in such situations.

III. Methodology

Study Design and Evidence Use

An analysis through simulation design was carried out to observe the behavior of two-timing metrics. The literature includes twelve purposely selected research articles from recent journal publications from 2022 to 2026. Searches based on topic included fresh water fish, spawning, reproductive phenology, variability of flow, flood pulse, and environmental flows. The publisher's databases and research repositories were searched for any relevance and bibliographical information on 10 November 2026. This purposive selection is not an exhaustive review and does not claim to be one. Articles were chosen if they discussed reproductive biology, migration timing, hydrological modification of spawning, egg/larvae transport, and response to flood pulses relevant to reproduction. No pooled effect size was estimated. Observations in the published works determined the choice of conceptual dimensions, while the values for scenarios were selected arbitrarily and did not match the articles. Figure 1 shows the analysis procedure.

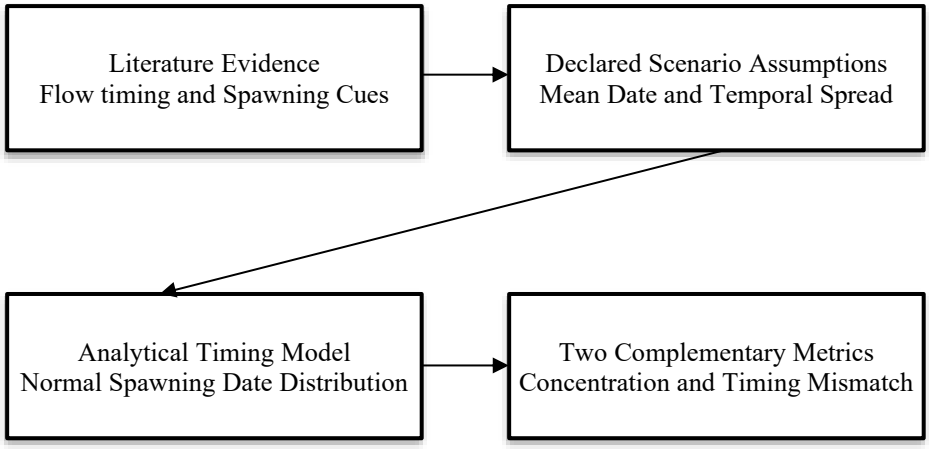


Figure 1: Framework for Assessing Spawning Concentration and Timing Mismatch

Synthetic Population and Timing Assumptions

The model shows a hypothetical seasonal spawning population in some undefined freshwater system. Let D represent the spawning date on a continuous day of year axis. Here, it is assumed that the distribution is normally distributed with mean μ and standard deviation σ. The habitat availability date H is taken as day 180, roughly corresponding to late June in a non-leap year. The positioning of habitat date is based on a model convention and not a habitat optimal as stated by the report. In all cases, population size, total reproductive effort, and habitat date remain constant. The model focuses on timing features only. The model does not incorporate any discharge time series, rainfall series, endocrine mechanism, organism identity, or survival process. Terms such as delayed or dispersed relate to shifts in the assumed spawning schedule and cannot be taken as observed outcomes of some flow change.

Distribution and Scenario Definitions

Definition of spawning date density is provided by equation 1. A continuous distribution is not susceptible to the problem of rounding when an event occurs between two calendar days. As all chosen means tend to lie close to the center of the year and the maximum standard deviation is only 18 days, the probability of going out of the year scale is zero in the four scenarios discussed above.

$$f(d \mid \mu, \sigma) = exp[-(d - \mu)^2 / (2\sigma^2)] / [\sigma\sqrt{(2\pi)}] \quad (1)$$

The aligned scenario assumes that μ is equal to 180 and σ = 7. In the case of the delayed scenario, μ changes to be 201, while σ remains equal to 7. The dispersed scenario assumes that μ = 180 and σ = 18. The combination scenario employs both μ = 201 and σ = 18. Such a two-by-two approach allows differentiating between the displacement of the date and timing variance.

Metric One Spawning Concentration

Concentration index C_{14} refers to the proportion of events that occur during a fourteen-day period with the mean value of the distribution. Large index means a higher concentration on that particular time scale. However, the interval is always centered at the mean of each situation, therefore, only displacement does not influence the index. Equation 2 defines the exact value of the index for the adopted normal distribution.

$$C_{14} = 100 \times P(\mu - 7 \leq D \leq \mu + 7) = 100 \times [2\Phi(7/\sigma) - 1] \quad (2)$$

The two-week interval is an analytical convention, not a known biological standard. For comparisons, the same interval width must be used. In field studies, the interval can be chosen based on the reproductive biology of the organism being studied and the level of sampling resolution. The concentration is a descriptive statistic that does not directly quantify fertilization probabilities or fitness.

Metric Two Environmental Timing Mismatch

Mismatch M is the distance between the average date of spawning and the centre of the habitat opportunity period as per equation 3, expressed in days. The smaller the figure, the greater the proximity. The absolute distance cannot tell which activity takes place after or before the other; hence, the signed distance is required for practical purposes.

$$M = |\mu - H|, with\ H = 180\ days \quad (3)$$

All calculations are done analytically using the normal cumulative distribution function and rounded up to two decimal places for concentration and whole days for mismatch. There is no random sample, seed, significance test, confidence interval, or empirical sample size in this problem. The sensitivity analysis consists of varying the interval and the date of the habitat while keeping the given spawning distributions constant.

IV. Results

Contrasting Concentration and Environmental Alignment

Table 1: Analytical Results For Four Synthetic Spawning Scenarios

Scenario	Mean date (day of year)	Spread σ (days)	C_{14} (%)	Mismatch (days)
Aligned	180	7	68.27	0
Delayed	201	7	68.27	21
Dispersed	180	18	30.26	0
Combined	201	18	30.26	21

Table 1 gives details of the four hypothetical scenarios and corresponding results from the analysis. Scenario alignment yields a concentration of 68.27% and mismatch of 0 days. Mismatch will be increased

to 21 days when keeping concentration as 68.27%, but increasing mean spawning date to 201 days, without changing the spread. Hence, spawning concentration does not necessarily imply spawning alignment.

Raising the standard deviation from 7 to 18 days lowers the concentration to 30.26%. The absolute difference is 38.00 percentage points, which represents a relative difference of about 55.67%. Since the dispersed case still has the mean equal to 180 days, it has a mismatch of 0 days. Hence, mean alignment may occur simultaneously with a wide distribution of reproductive events. The compound case has a concentration of 30.26% and mismatch of 21 days. These are exactly the same as the dispersed and delayed cases, respectively, since the two statistics depend on different parameters in the current model. This independence is a mathematical feature of the model formulation. It does not imply biological independence of the two features in actual fish populations.

What the Contrast Establishes

Classification by concentration alone will place aligned spawning in the category of delayed spawning and dispersed spawning in the category of combined spawning. On the other hand, classification by mismatch alone will place aligned spawning in the category of dispersed spawning and delayed spawning in the category of combined spawning. The use of either ranking alone will not classify all four timing categories. It is important to provide both rankings to maintain data that would otherwise be lost when using one ranking alone. None of the scenarios receives a reproductive success ranking. For example, 68.27% is a ranking of concentration within a certain time period and should never be referred to as survival, recruitment, accuracy, or successful fertilization.

Graphical Comparison of the Two Metrics

Figure 2 presents the scenario outputs on different axes but retaining the original units. The concentration curve is affected by the spread of time, while the discrepancy curve is affected by the change in the mean date. The lines link different scenarios and do not represent a chronology of events or a response to increased river discharge.

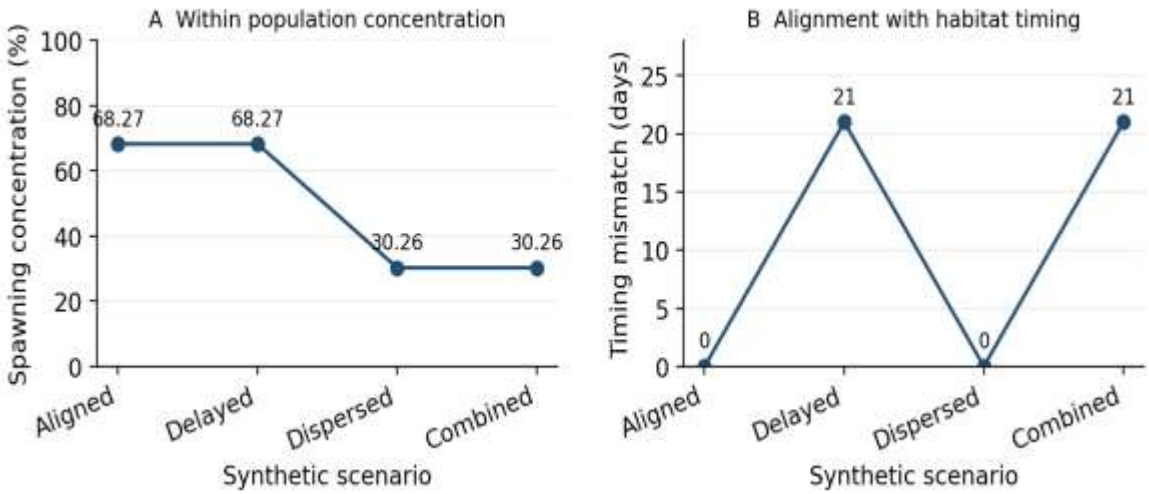


Figure 2: Scenario Comparison Through Synthetic Scenarios using Two Different Measures. Panel A: Spawning Concentration Within 14 Days Centered Around Each Scenario Mean. Panel B: Absolute Difference from Habitat at Day 180

Sensitivity to Metric Definitions and Habitat Assumptions

For a seven-day window around the mean, concentrations are 38.29% with $\sigma = 7$ and 15.42% with $\sigma = 18$. For a twenty-eight-day window, the respective concentrations are 95.45% and 56.33%. An increase in the interval leads to increases in both concentrations while maintaining their ranking order. The absolute

measures of concentrations are thus dependent on an explicit interval specification. There is no cut-off point differentiating between synchronous and asynchronous breeding in any of the examples above. By changing the habitat opportunity date from day 180 to 187, mismatch becomes 7 days for the aligned and dispersed scenarios, and 14 days for the delayed and combined scenarios. With H = 201, the ranking of central alignment is reversed, with mismatch becoming 0 for the delayed and combined scenarios, and 21 days for the remaining two scenarios. Mismatch value is therefore dependent on the habitat opportunity definition. This test shows that each of the two dependencies is based on a different factor. The dependency of concentration is affected by both the time scale chosen and the spawning pattern. The dependency of mismatch is influenced by the reference environment that is chosen independently. Any improvement in either measure can be attributed to the change in its definition rather than an improvement in ecological conditions.

V. Discussion

Analysis of contrasts is between intra-population synchronization and environmental synchronicity. Together, they can contribute to an analysis of the suggested release flow. A very short pulse during spawning may be out of sync, and a good mean time may include wide variation among individuals. This does not prove any consistent biological reaction. The flow components and the thermal factors need to be analyzed for each specific species. Biological maturity, habitat availability, and the situation after egg discharge must be considered along with timing criteria. Release schedule also needs an independent analysis of magnitude, duration, and recession (Yu et al., 2023; Griffen & Weber, 2025; Lv et al., 2023).

Use of these metrics involves specific spawning times or events that can be estimated, each year and site. Gonadal status is indicative of maturity, fishways indicate passage, and larval captures indicate spawning with prior adjustments for transport and detection. These observations are not interchangeable as equivalent dates (Bezbaruah et al., 2025; Stuart et al., 2026; Mariac et al., 2022). When larval back calculations are applied, the time of development, temperature effects, and drift should be incorporated into timing estimates (LeRoy et al., 2024). There are several limitations of the approach. The normal distribution has only one mode and is symmetrical; on the other hand, fish populations can have more than one cohort, batch spawning, timing differences, and even calendar differences between males and females. One single habitat date does not consider the temporal availability of habitats and quality of nursery conditions. Neither of the two metrics estimates the percentage of eggs reaching appropriate habitats and recruits being formed from these eggs. The future research should investigate other possible distributions and opportunity for habitats to occur independently.

VI. Conclusion

This analytical evidence-based study shows the difference between reproductive concentration and environmental timing mismatch in fresh water fish, which allows the assessment of two complementary aspects of spawning phenology. With the clearly stated synthetic assumptions, extending the temporal dispersion of spawning from 7 to 18 days decreases the percentage of spawning within a period of 14 days from 68.27% to 30.26%. On the other hand, moving the spawning curve by 21 days increases its mismatch with the environment by 21 days without changing reproductive concentration. The results obtained through computation show that temporal dispersion and temporal displacement are different parameters, and each one alone can miss an important aspect of reproduction timing. The findings, however, are derived from controlled analytical experiments and should not be seen as any form of proof regarding causation, hydrologic effects, ideal flows, or reproductive success. Application in a real-life river would call for species-specific spawning data, an independent reference of proper habitat timing, and validation based on reproductive success. Future studies will need to consider issues of uncertainty, seasonality, and interspecific variation before making any management decisions. This study framework is hence a clear point of departure for incorporating spawning concentration and environmental alignment into freshwater ecological studies.

References

[1] Röpke, C., Pires, T. H., Zuchi, N., Zuanon, J., & Amadio, S. (2022). Effects of climate-driven hydrological changes in the reproduction of Amazonian floodplain fishes. *Journal of Applied Ecology*, *59*(4), 1134-1145. https://doi.org/10.1111/1365-2664.14126

[2] Yu, Y., Zhao, R., Zhang, J., Du, S., Zhou, T., Fu, X., & Jiang, S. (2023). Identification and restoration of hydrological processes alteration during the fish spawning period. *Scientific Reports*, *13*(1), 11307. https://doi.org/10.1038/s41598-023-38441-x

[3] Griffen, E. M., & Weber, M. J. (2025). Environmental factors associated with fish reproduction in regulated rivers. *River Research and Applications*, *41*(2), 515-530. https://doi.org/10.1002/rra.4376

[4] Bano, F., Mishra, H., Kantharajan, G., Kanaujiya, S., Singh, R. K., & Sarkar, U. K. (2025). Unravelling reproductive biology of the striped gourami, Trichogaster fasciata (Bloch and Schneider, 1801) with reference to climate change and implications on breeding phenology in Ganges basin, India. *International Journal of Biometeorology*, *69*(7), 1557-1568. https://doi.org/10.1007/s00484-025-02911-w

[5] Rahman, M. A., Sultana, M. A., Ahmed, F. F., & Hossain, M. Y. (2024). Effect of water quality parameters and climatic influences on reproductive phenology of Macrognathus pancalus in wetland ecosystem: recommending a long-term management approach and conservation policy. *Environmental Monitoring and Assessment*, *196*(2), 219. https://doi.org/10.1007/s10661-024-12364-0

[6] Bezbaruah, H. K., Mogalekar, H. S., Raut, S. M., Ram, R. K., Nayak, S. K., Gupta, B. K., & Sahu, B. (2025). First study on habitat ecology, biometric parameters and biology of Rita rita (Hamilton, 1822) from tropical perennial River Burhi Gandak, India. Environmental Monitoring and Assessment, 197(5), 568. https://doi.org/10.1007/s10661-025-14042-1

[7] Deng, Q., Sabo, J. L., Holtgrieve, G. W., Ngor, P. B., & Holway, J. (2023). Timing of hydrologic anomalies direct impacts on migration traits in a flood pulse fishery system. *Journal of Applied Ecology*, *60*(3), 494-506. https://doi.org/10.1111/1365-2664.14349

[8] Stuart, I. G., Thiem, J. D., & Fanson, B. G. (2026). Flow-Regulated Migration Phenology of Potamodromous Fishes in a Large Regulated Australian River. *Freshwater Biology*, *71*(8), e70292. https://doi.org/10.1111/fwb.70292

[9] Mariac, C., Renno, J. F., Vigouroux, Y., Mejia, E., Angulo, C., Castro Ruiz, D., ... & Duponchelle, F. (2022). Species-level ichthyoplankton dynamics for 97 fishes in two major river basins of the Amazon using quantitative metabarcoding. *Molecular Ecology*, *31*(6), 1627-1648. https://doi.org/10.1111/mec.15944

[10] LeRoy, J. Z., Doyle, H. F., Jackson, P. R., & Cigrand, C. V. (2024). Reproduction of grass carp (Ctenopharyngodon idella) in the Maumee River, Ohio: Part 2—Optimal river conditions for egg and larval drift. *Journal of Great Lakes Research*, *50*(3), 102345. https://doi.org/10.1016/j.jglr.2024.102345

[11] Lv, X., Yang, Z., Hu, P., Wang, W., Zeng, Q., & Yan, X. (2023). Quantifying environmental flow in the form of pulse flow for fish protection. *Water*, *15*(15), 2820. https://doi.org/10.3390/w15152820

[12] Kelkar, N., Arthur, R., Dey, S., & Krishnaswamy, J. (2022). Flood-pulse variability and climate change effects increase uncertainty in fish yields: Revisiting narratives of declining fish catches in India's Ganga River. *Hydrology*, *9*(4), 53. https://doi.org/10.3390/hydrology9040053