THE INCLUSIVE STUDY ON POSSIBLE IMPROVEMENT OF THE MEKONG FLOW FRAMEWORK

PART 1

Reviewing PMFM thresholds and existing Mekong flow frameworks

June 2023

Technical Support

Australian Aid

eWater solutions

Revisiting PMFM and identifying and evaluating potential new implementable flow thresholds (and methodologies) for guiding the monitoring and management of flow conditions in the mainstream

The Inclusive Study on Possible Improvement of the Mekong Flow Framework Part 1

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June 2023

Mekong River Commission (MRC)

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Executive Summary

The Mekong River Commission (MRC) recognises the significance of river monitoring and flood/drought forecasting and river basin planning in assessing and managing water resources within the Mekong River Basin. Key to these activities is the **River Flow Framework** or **Hydrological Indicators**. These indicators provide essential information about the state and trends of water resources, enabling effective water management strategies and ensuring the health and functionality of river ecosystems. By leveraging these tools, the MRC aims to promote sustainable water resource management in the Mekong River Basin.

The main objective of this work is to explore approaches and methodologies for an alternative flow framework and a development of a web-based Mekong flow monitoring tool to support river monitoring and implementation of the PMFM. To accomplish the aforementioned objective, this study encompasses four essential steps:

- **Reviewing and exploring the development of an alternative flow framework** (this report): This step involves the comprehensive examination of existing approaches to river monitoring within the MRC systems and other river management organisations. It also entails further exploring an enhanced flow framework to develop a web-based Mekong flow monitoring tool.
- **Developing an approach and methodology to quantify the alternative flow framework**: This step focuses on the formulation of a systematic approach and methodology for quantifying and implementing the alternative flow framework. It aims to establish reliable techniques to measure and analyse the flow data effectively.
- **Developing a web-based river monitoring and visualisation platform**: This step involves the creation of a user-friendly and web-based platform for river monitoring and visualisation. The platform will enable easy access to near real-time and historical river flow data, enhancing data interpretation and decision-making processes.
- **Proposing workflows and conducting capacity building**: This step entails the formulation of efficient workflows and procedures for effectively utilising the developed tools and platforms. It also involves conducting capacity building initiatives to empower stakeholders with the necessary skills and knowledge to utilise the tools and understand the river monitoring process.

The Member Countries' guidance on implementing the PMFM

The national consultation meetings on updating the flow framework for the PMFM provided useful feedback for revisiting flow thresholds and methodologies. The outcomes highlighted the priorities and directions identified by the Member Countries, contributing to the development of an appropriate framework for the monitoring and planning purposes.

This collaborative process ensures that the flow framework is tailored to the specific needs and requirements of the Lower Mekong Basin, promoting effective and harmonised implementation of the PMFM across all Member Countries.

Key recommendations include data verification, whole year reporting, rapid water level variation, and the use of existing threshold methodologies. Stakeholder engagement, validation of simulated flow, and consideration of hydropower cascade impacts were also suggested. Moreover, it is critical to align the flow framework with emergency plans of water infrastructure, establish suitable thresholds at tidal stations, and prioritise capacity building.

Commonly used hydrological indicators

While these findings offer valuable insights, it is essential to note that further investigation and analysis are necessary to understand the complexities and nuances of each parameter when applying to real datasets of the Mekong mainstream and Tonle Sap Lake.

From an extensive review of the peer-reviewed scientific articles, some indicators are commonly used across studies to analyse and compare flow variations over a range of temporal scales. They are identified and listed below for possible adaptation in the Mekong context. These are seemingly simple indicators and do not involve complex calculations.

- **Mean flow** for a month, season, year or day of the year is the average flow for the period of interest and is calculated by dividing the sum of daily flows by the number of daily flows recorded for the year. This is a hydrological indicator used commonly to represent and compare flow magnitudes. In addition to the mean flow, there are other indicators of hydrologic alteration (IHA) which are used to represent flow magnitudes. They are minimum and maximum for 1-day, 3-day, 7-day, 30-day, and 90-day durations. These indicators can be used to compare the high and low flow magnitudes for various durations across years.
- **Flow percentiles** are used to compare the magnitudes of low and high flows. For example, the 90th percentile (Q10) flow is the flow which was equalled or exceeded for 10% of the specified duration (UKCEH,2022). According to USGS (2022), a percentile greater than 75 is considered above normal, a percentile between 25 and 75 is considered normal and a percentile less than 25 is considered below normal. Based on the long-term flow trends of Mekong, suitable flow percentiles may be selected to set flow thresholds.
- **Baseflow** is defined as the streamflow component contributed by subsurface storage and it sustains the river flow during dry seasons and droughts (Bloomfield et al., 2021). Knowledge and information about baseflow are critical to separate the streamflow hydrographs, especially to know the surface flow contributions before and after hydrologic alterations. This is important in the context of identifying the causes of drought in the Lower Mekong Basin (LMB) during 2019-2020. Also, baseflow trends can be used to identify unsustainable catchment management practices (Kelly et al., 2019).
- **Baseflow Index (BFI)** is the ratio of baseflow to the total streamflow and it gives an indication of the contribution of sub-surface flows, mainly groundwater to the river flows. Many of the above-mentioned papers used BFI as an indicator for flow monitoring.
- **Flow Duration Curves (FDC)** can be used to compare the flow thresholds between two periods. Aspects of FDC such as FDC slope can be used to indicate the rate of change of flows. Concepts such as ecostatistics (ecodeficit and ecosurplus) can be calculated using FDCs related to different periods and thus evaluate the impacts of river regulations. In the Mekong context,

FDCs can be used to compare the exceedance values of flows between months, seasons or years.

- **Rise and fall rates** indicate the rate of change of flows and river levels. Rise rate is the mean rate of positive changes in flow or level from one day to next. Fall rate is the mean rate of negative changes in flow or level from one day to the next. The unit of rise and fall rate indicator is m/d. The rise and fall rates of two periods (for example, pre- and post-commissioning of dam) can be compared to inform the changes in flow or level.
- **Rising and falling limb densities** are also indicators used to measure the rate of flow or level change. As mentioned earlier, they are ratios of the number of rising or falling limbs to the total time of rising or falling limbs. The recent patterns of rising and falling limb densities can be compared with that of long term or pre-development ones to evaluate changes if any.

Furthermore, the following indices are correlated to catchment-specific characteristics such as climate, topography and vegetation. They are helpful in identifying the drivers of streamflow hydrographs.

- **Number of fluctuations/reversals** is a metric showing the number of positive and negative changes in water conditions from one day to the next.
- **Frequency of low and high pulses** shows the number of low flows (usually < 25^{th} percentile discharge) or high flows (usually > 75^{th} percentile discharge) in a year.
- **Duration of zero, low and high pulses** presents the number of consecutive days with zero, low and high flows. The low and high flow thresholds are set based on the site-specific characteristics.
- **Spell analysis plots** illustrate the frequency and duration of flows above or below a threshold value. Such plots can be part of the MRC flow monitoring tool to show the duration of a high or low flow per year for a period of record.

Inspiration for water dashboard design

The web-based tools and dashboards reviewed in this report provide valuable insights that can be adapted to enhance the design of the Mekong water dashboard. Platforms like the **USGS WaterWatch** offer a straightforward approach, enabling users to access multiple features from a single page. The **USGS National Water Dashboard** also provides a comprehensive platform that presents the current flow status compared to historical flows.

The recent update of the MRC landing page brings a more unified visualisation, improving communication with stakeholders. However, the web pages for the main products and services are spread across different sites, creating a fragmented user experience. More specifically, the near real-time hydrometeorological monitoring page displays in map and list formats. Selecting a station provides detailed information, including hydrographs and rainfall trends. Other MRC webpages present flood and drought information and forecasts, while the PMFM webpages is illustrated on a separate website. It would be advantageous to have a single, comprehensive flow monitoring dashboard that consolidates all flow information and facilitates easy navigation.

Drawing inspiration from the flow frameworks of other organisations, particularly the USGS WaterWatch dashboard, selected features can be integrated to illustrate the flow frameworks for the MRC. By exploring technology adoption options, the MRC can prioritise simplicity and ease of future maintenance and operation, avoiding unnecessarily complex processes.

Way forward

Moving forward, the activity will embark on the following steps

- **Gathering country's perspective on PMFM thresholds**: The activity will continue to engage with the Member Countries to understand their perspectives on updating the PMFM thresholds. This feedback will be valuable in guiding the refinement of the thresholds.
- **Refinement of the list of parameters**: The report will be revised to present the information concisely. Input from the Member Countries are sought to ensure the report accurately reflects their perspectives and feedback. The MRC Secretariat will further develop and refine the list of parameters to be used in conjunction with the Mekong dataset. This step will ensure that the selected parameters are appropriate and relevant for the specific context of the Mekong region.
- **Initial design of a web-based tool for Mekong Flow Monitoring**: An initial design of a web-based tool will be drafted to facilitate data visualisation and analysis. This tool will provide a user-friendly interface for accessing and interpreting the information related to the flows on the Mekong River system. Additionally, the activity will explore the potential integration of the tool with the upgrade of the Decision Support Framework (DSF), enhancing its capabilities and functionality.

1 Introduction

The Mekong River is one of the longest rivers in Southeast Asia, stretching over 4,900 kilometres and flowing through six countries: China, Myanmar, Lao PDR, Thailand, Cambodia, and Viet Nam. The river basin supports the livelihoods of millions of people, providing water for irrigation, hydropower generation, fisheries, and transportation. River monitoring and flood/drought forecasting are crucial activities for the Mekong River Commission (MRC) undertaken to assess and manage the water resources in the Mekong River Basin.

Flow monitoring in the Mekong River involves continuously measuring and analysing water levels and discharges at various gauging stations along the river. These gauges, equipped with staff reading, sensors and instruments, provide manual data and real-time data collection on water flow, which is essential for understanding the hydrological conditions of the river. The data collected from flow monitoring stations helps assess the overall water availability, identify trends, and detect anomalies such as floods or droughts or rapid flow variation.

Flood forecasting aims to predict and issue early warnings about potential flood events in the Mekong River Basin. It involves using hydrological models and historical data to simulate the behaviour of the river during heavy rainfall or rapid snowmelt. The MRC Secretariat can estimate the potential flood risks downstream and provide timely alerts to the MRC Member Countries and communities living in the affected areas by analysing the upstream inflows, rainfall patterns, and other relevant factors. This information allows the Member Countries to implement evacuation plans, deploy emergency response measures, and minimise the impact of floods on people and infrastructure.

Similarly, drought forecasting focuses on predicting periods of extended dryness and water scarcity in the Mekong River Basin. Droughts can severely affect the region's agriculture, water supply, and ecosystems. Drought forecasting involves monitoring precipitation patterns, river flows, soil moisture levels, and other climatic factors to assess the severity and duration of drought conditions. Early warnings enable governments, farmers, and local communities to plan and implement water conservation measures, crop diversification, and alternative livelihood options.

Furthermore, river flow monitoring supports basin planning for sustainable development. It provides critical information for designing and implementing water allocation policies, optimising hydropower generation, and managing water resources across different sectors. By understanding the flow dynamics, national authorities can make informed decisions regarding reservoir operations, water diversions, and the establishment of environmental flow regimes that maintain the ecological integrity of rivers.

Flow monitoring and flood and drought forecasting in the Mekong River Basin are typically carried out through collaborative efforts between regional organisations, national governments, and international partners.

River Flow Framework or **Hydrological Indicators** play a important role in river monitoring, river flood and drought forecasting and river basin planning, providing valuable information about the status and trends of water resources in the basin. These indicators serve as essential tools for assessing the health and functionality of river ecosystems and supporting effective water management strategies.

The **Vientiane Declaration, titled "Innovation and Cooperation for a Water Secure and Sustainable Mekong"**, issued on April 5, 2023, urges the MRC, partners, and stakeholders to address challenges and embrace opportunities through innovative solutions. The declaration emphasises the importance of cooperation, openness, transparency, inclusiveness, mutual benefits, equality, consultation, coordination, cooperation, and respect for sovereignty in achieving a water secure and sustainable Mekong River Basin. The below two priority areas of action listed in the Vientiane Declaration well aligned with our current work on development of update flow frameworks to support MRC Flow Monitoring Capability and Revisiting PMFM and identifying and evaluating potential new implementable flow thresholds:

- "*Enabling basin countries to support communities to adapt to changing river conditions by ensuring a more effective and timely communications and notification system for unusual water flows, water quality issues, flood and drought and other water-related emergencies both among basin countries and to the communities, and by working towards the increased sharing of operational data from water infrastructures in a timely and regular manner for better preparedness and response.*"
- "*Supporting development and operational decisions through improved use of technology, including enhanced decision support for the implementation of all river basin management functions from water-related monitoring and operational basin management to long-term strategic assessments and planning.*"

The **MRC Strategic Plan 2021-2025** has **Activity 1.1.1.1 Revisiting PMFM and identifying and evaluating potential new implementable flow thresholds (and methodologies) for guiding the monitoring and management of flow conditions in the mainstream**, under BDS Outcome 1.1: Adequate water flow and quality for a healthy environment and productive communities, in Strategic Priority 1: Maintain the ecological function of the Mekong River Basin. This strategic priority is to maintain the ecological function of the Mekong in good condition. This suggests the MRC focuses on supporting basin countries to improve the management of river flows in the mainstream and to mitigate the potential adverse impacts on the environment from water resources development.

Concerning water flows, the current technical guidelines for the **Procedures for the Maintenance of Flows on the Mainstream (PMFM)** are silent on minimum flows in the flood season, maximum flows in the dry season and rapid river level fluctuations (including due to climatic variability) that are of increasing concern to basin communities. Revisiting the PMFM to take account of these issues, and to finalise and implement the guidelines through notification and appropriate country actions will help improve community confidence in the management of the river and contribute to better environmental outcomes. Ensuring the adequate reverse flow and other important functions of Tonle Sap will also be considered based on the further study of the Lake's requirements

The main objective of the **Technical Guidelines** on the implementation of the PMFM is to provide flow frameworks (and associated thresholds) for the implementation of the PMFM for planning and real time monitoring purposes at each of the selected hydrological stations, with a view to:

- for **Planning purposes** – to assess a development scenario (as part of MRC's strategic planning cycle) or proposed project (under the PNPCA) to inform national and transboundary planning, decision-making and governance processes; and
- for **Monitoring purposes** – to raise awareness of real time flow conditions (as part of MRC's hydrological monitoring) and discuss whether coordinated action by the Member Countries is needed.

Alternative flow frameworks also aligned with Mekong River Basin Indicator Framework and redesign of Core River Monitoring Network. The design of the **Mekong River Basin Indicator Framework (MRB-**

IF) was guided by two overarching goals: (1) The Indicator Framework must support cost-effective data generation by the Mekong River Commission Secretariat and Member Countries over the long term and (2) The Indicator Framework must enable an assessment of status and trends in conditions across the whole of the basin, while also allowing for scenario assessments at different spatial and temporal scales as appropriate to the particular circumstances. To uphold the MRB-IF Strategic Indicator of water flow conditions in the mainstream, the MRB-IF Assessment Indicators primarily rely on the PMFM. These assessment indicators include:

- Compliance of dry season flows with the PMFM
- Compliance of flood season peak flows with the PMFM
- Compliance of Tonle Sap Reverse Flow with the PMFM
- Change in the timing of onset of wet season flows

Furthermore, the **Core River Monitoring Network (CRMN)** redesign will provide data for the five environmental disciplines (hydrology, sediments, water quality, ecological health and fisheries). The redesign builds on a comprehensive methodology that incorporates the following key elements:

- An objective network optimisation using an iterative algorithm based on the criteria the CRMN should meet.
- Some finetuning of the stations to interpret and adapt the optimisation outputs.

The development of the alternative flow frameworks and revisiting PMFM flow thresholds support to the initiative of the **reinvigoration project**, where MRC adopted four main components of (1) data and information collection and acquisition, (2) data and information management, (3) data and information processing, and (4) data and information visualisation.

1.1 Objectives

The main objective of this work is to explore approaches and methodologies for an alternative flow framework and a development of a web-based Mekong flow monitoring tool to support river monitoring and implementation of the PMFM. To accomplish the aforementioned objective, this study encompasses four essential steps:

- **Reviewing and exploring the development of an alternative flow framework** (this report): This step involves the comprehensive examination of existing approaches to river monitoring within the MRC systems and other river management organisations. It also entails further exploring an enhanced flow framework to develop a web-based Mekong flow monitoring tool.
- **Developing an approach and methodology to quantify the alternative flow framework**: This step focuses on the formulation of a systematic approach and methodology for quantifying and implementing the alternative flow framework. It aims to establish reliable techniques to measure and analyse the flow data effectively.
- **Developing a web-based river monitoring and visualisation platform**: This step involves the creation of a user-friendly and web-based platform for river monitoring and visualisation. The platform will enable easy access to near real-time and historical river flow data, enhancing data interpretation and decision-making processes.
- **Proposing workflows and conducting capacity building**: This step entails the formulation of efficient workflows and procedures for effectively utilising the developed tools and platforms. It also involves conducting capacity building initiatives to empower stakeholders with the necessary skills and knowledge to utilise the tools and understand the river monitoring process.

The alternative flow framework could be used to evaluate the status of flow conditions and their changes compared to past conditions. Aligned with the reinvigoration exercise and closer integration with other initiatives of upgrade MRC systems, the web-based river monitoring would support to update of the visualisation of MRC flood and drought webpages and upgrade of MRC Decision Support Framework (DSF) and implementation of the PMFM.

1.2 Scope of work

The scope of the work includes the following aspects:

- **Parameter**: The focus is on monitoring water level and derived discharge, which are crucial indicators of river flow.
- **Magnitude**: The monitoring encompasses the full range of flow variability, including high and low flow conditions.
- **Spatial scale**: The monitoring covers the Mekong mainstream and Tonle Sap Lake, ensuring comprehensive coverage of key areas within the river basin.
- **Temporal scale**: The monitoring conducts year-round, encompassing two distinct seasons: the wet season and the dry season. This approach allows for a comprehensive understanding of flow patterns throughout the year.
- **Period of interest**: The monitoring aims to explore long-term data from the 1960s to present. For instance, the static period gives a comprehensive comparison between present flow conditions to historical period before major hydrological changes, while the dynamic period compares the present flow condition to more recent river conditions.

2 Existing flow frameworks

2.1 The Procedures for the Maintenance of Flows on the Mainstream

In their **1995 Mekong Agreement**, the Lower Mekong Basin (LMB) Countries of Cambodia, Lao PDR, Thailand and Viet Nam established the MRC and agreed to "*cooperate in all fields of sustainable development, utilisation, management and conservation of the water and related resources of the Mekong River Basin.*" A rolling Basin Development Plan and the MRC Procedures are primary instruments for that cooperation. The procedures are an integral part of MRC's five-year planning cycle.

The MRC initiated the Water Utilisation Programme (WUP) in 1999, to develop sets of rules for water utilisation in the LMB. The following are the five MRC Procedures:

- Procedures for Data and Information Exchange and Sharing (PDIES) – 2001,
- Procedures for Water Use Monitoring (PWUM) – 2003,
- Procedures for Notification, Prior Consultation and Agreement (PNPCA) – 2003,
- Procedures for the Maintenance of Flows on the Mainstream (PMFM) – 2006,
- Procedures for Water Quality (PWQ) – 2011.

The Procedures for the Maintenance of Flows on the Mainstream (PMFM) aim at protecting the natural flow regime. In **Article 6** of the 1995 Mekong Agreement, the LMB Countries agreed "*to cooperate in* *the maintenance of the flows on the mainstream from diversions, storage releases, or other actions of a permanent nature, except in the cases of historically severe droughts and/or floods:*

- *Article 6A: Of not less than the acceptable minimum monthly natural flow during each month of the dry season;*
- *Article 6B: To enable the acceptable natural reverse flow of the Tonle Sap River to take place during the wet season; and*
- *Article 6C: To prevent average daily peak flows greater than what naturally occur on the average during the flood season.*"

The principles of the PMFM as described in the 1995 Mekong Agreement cannot be fully implemented right away. They lack essential information such as the acceptable water flows to be maintained and how this will be done. This information has been developed by expert groups with members of the LMB Countries. They studied and discussed a range of implementation options that resulted in two negotiated documents:

- Procedures for the Maintenance of Flows on the Mainstream (PMFM); and
- Draft Technical Guidelines on Implementation of the PMFM.

The MRC Council adopted **the Procedures for the Maintenance of Flows on the Mainstream** on 22nd June 2006. They have the central objective of providing a framework for technical guidelines, institutional arrangements, directions and information to enable the MRC and its Member Countries to maintain the flows of the Mekong River mainstream as required by the 1995 Mekong Agreement. The Procedures are presented in seven main sections (Box 1). They are to apply to diversions, storage releases, or other actions of a permanent nature undertaken by the Member Countries, which may have a significant impact on the flows of the mainstream during the wet and dry seasons in accordance with Article 6 of the 1995 Mekong Agreement.

The Procedures reaffirm the requirements of Article 6 and confirm that separate Technical Guidelines are to be prepared to, inter alia: determine the levels of the flows to be maintained and to establish criteria for selection of hydrological stations required for the implementation of the Procedures.

The (working version) **Technical Guidelines** on the PMFM has been developed after extensive consultation between representatives of the Member Countries within the Technical Review Group (TRG), established by the MRC Joint Committee for this purpose in 2003.

It is clear that the TRG made considerable progress on the drafting of the Technical Guidelines for the PMFM. The first draft Technical Guidelines were prepared based on the 2004 hydrological assessment and MRC Integrated Basin Flow Management (IBFM) completed in September 2006. In particular, an acceptable flow frameworks has been determined for:

Box 1. Contents of the Procedures for the Maintenance of Flows on the Mainstream.

Preamble

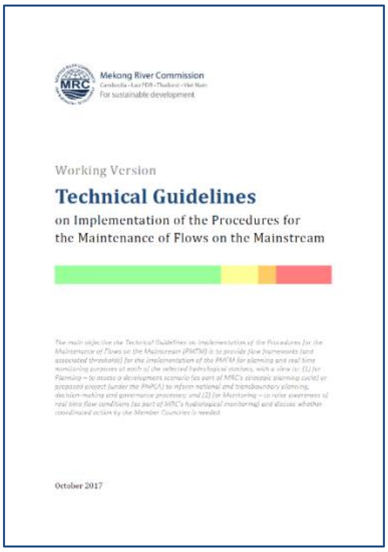
1. **Definitions**
2. **Objectives**
3. **Principles**
4. **Scope**
5. **Maintenance of flows on the mainstream**
    - Flows to be maintained
    - Hydrological stations
    - Preparation, review and revision of the Technical Guidelines
6. **Institutional arrangements**
    - MRC Council
    - MRC Joint Committee
    - MRC Secretariat
    - National Mekong Committees
7. **Final provisions**
    - Amendments or modifications
    - Entry into force

- **Planning purposes**: flow frameworks against which future basin-wide development scenarios or projects can be assessed; and

- **Monitoring purposes**: flow frameworks that can be used to validate the predictions made for the PMFM for planning purposes and to raise awareness of daily flows and to discuss coordinated action by the Member Countries whenever needed.

By the end of 2006, the TRG had reached a working agreement on five of the six flow frameworks that are required for the implementation of the PMFM. In the following years, the PMFM activities focussed on the discussions of possible flow frameworks for the implementation of Article 6A for planning purposes, which constitutes the main pending issue. In parallel, successive drafts of the Technical Guidelines were prepared and discussed.

The 10th TRG Meeting (5 October 2011), whilst recognising that differences of opinion remained amongst the Member Countries with respect to the definition of a minimum flow framework for planning purposes, agreed to implement the draft Technical Guidelines on an interim basis by testing the flow frameworks as set out in the draft Technical Guidelines of October 2011. They further agreed to implement the draft Technical Guidelines in a learning-by-doing approach.

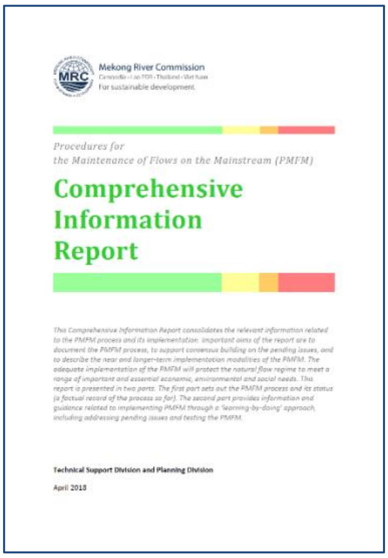


The draft Technical Guidelines of October 2011 state that Technical Guidelines will be reviewed every five years and be first updated in 2015, or earlier if the TRG considers that there is clear evidence that the flow frameworks or the implementation arrangements need to be modified. The 35th MRC Joint Committee Meeting (April 2012) acknowledged that the draft Technical Guidelines of the PMFM can be implemented in a learning-by-doing approach, including the testing of the considered alternative flow frameworks for Article 6A for planning purposes.

In recent years, three key documents have been instrumental in recording the progress and implementation of the PMFM.

PMFM Implementation Report: This report, prepared by the PMFM Technical Review Group, summarises the outcomes and experiences of implementing the PMFM using a learning-by-doing approach from 2011 to 2015. It provided valuable insights to finalise and adopt the draft Technical Guidelines for PMFM implementation.

PMFM Technical Guidelines: The primary objective of these guidelines is to establish flow frameworks, including associated thresholds, for implementing the PMFM. They serve two main purposes: (1) for planning, by assessing development scenarios or proposed projects to inform national and transboundary planning, decision-making, and governance processes within the MRC's strategic planning cycle or under the PNPCA, and (2) for monitoring, by raising awareness of near real-time flow conditions as part of the MRC's hydrological monitoring, and facilitating discussions on the need for coordinated actions among Member Countries.



PMFM Comprehensive Information Report: This long report consolidates relevant information on the PMFM process and its implementation. It aims to document the PMFM process, foster consensus-building on pending issues, and describe the near and long-term modalities for implementing the PMFM. The report emphasises the importance of effectively implementing the PMFM to protect the natural flow regime, vital in meeting significant economic, environmental, and social needs. It is presented in two parts: the first part provides a factual record of the PMFM process and its current status, while the second part offers information and guidance on implementing the PMFM through a learning-by-doing approach, including addressing pending issues and conducting PMFM tests.

The MRC uses a combination of flow monitoring tools and frameworks to inform the stakeholders and public about the near real-time flow conditions in the Mekong River. These flow monitoring frameworks use water level and derived discharge data to compare the current river flow conditions with past flows against a set of indices.

The flow frameworks at MRC are governed by the PMFM. Article 6 of the 1995 Mekong Agreement defines the hydrological criteria for the maintenance of flows in the Mekong River. Under Article 6, there are three sub-articles which set monitoring parameters to monitor the flows and determine the actions to be taken. Monitoring parameters are essentially processed or calculated data, which enable the evaluation of assessment indicators. For example, the monitoring parameters which enable the flow monitoring assessment indicators are daily dry and wet season water levels and discharges relative to various Annual Recurrence Interval (ARI) levels. Thus, the parameters assist in quantifying the river flow conditions and compare and maintain the flows at different spatial and temporal scales along the Mekong. These articles (6A, 6B and 6C) set the rules for the acceptable flows on the Mekong mainstream during the dry and wet seasons and acceptable natural reverse flows of the Tonle Sap Lake as indicated in Figure 1. The following sections describe the articles for flow monitoring on the mainstream during wet and dry periods and Tonle Sap.

Criteria on Water Flow

River	Season	Type of Flow to maintain	Flow Assessment Criteria for Monitoring	Flow Assessment Criteria for Planning
Mekong River	Dry	Minimum monthly flow	A set of minimum daily flow	A set of minimum monthly flow
	Flood	Maximum daily peak flow	A set of maximum daily flow	A set of maximum monthly flow
Tonle Sap River	Wet	Reverse flow	A range of historical daily flow at Prek Kdam	A range of seasonal flow at Kratie

Figure 1. Criteria on water flow with the seasons defined in the PMFM (MRC, 2018).

2.1.1 Article 6A – Flow monitoring during the dry season

Article 6A deals with the acceptable minimum monthly natural flow during the dry season of the year, which is from December to May (MRC, 2022a). This framework is based on the daily observed water level and derived discharge, usually from 1960 to 2010 at recurrence intervals ranging from 1:5 to 1:20 ARI at selected hydrological stations. The flows are compared to various ARI levels to indicate significant or critical departures below the normal or acceptable levels (MRC, 2018). The flow monitoring rules as per Article 6A are given in the Table 1 . Accordingly, the categories are set as four zones according to various levels of ARI and the hydrological conditions are assigned for each zone. Then the actions which needed to be taken are enlisted.

Table 1. Flow monitoring during the dry season as per Article 6A (MRC, 2018).

Zone	If the daily flow is...	Hydrological condition	Action
Zone 1 (green)	Above ARI 1:5	Normal	No need for action
Zone 2 (yellow)	Between ARI 1:5 and ARI 1:10	Stable	Need for caution
Zone 3 (orange)	Between ARI 1:10 and ARI 1:20	Unstable	Investigation needed to identify plausible causes. There is a need to be alert
Zone 4 (red)	Below ARI 1:20	Severe	Consider implementation of mitigating measures

A snapshot of the visualisation of the dry season monitoring using Article 6A is shown in Figure 2 below. The figure illustrates the rated discharge plotted against minimum, maximum, average and different zones discharges at a station named Chiang Saen.

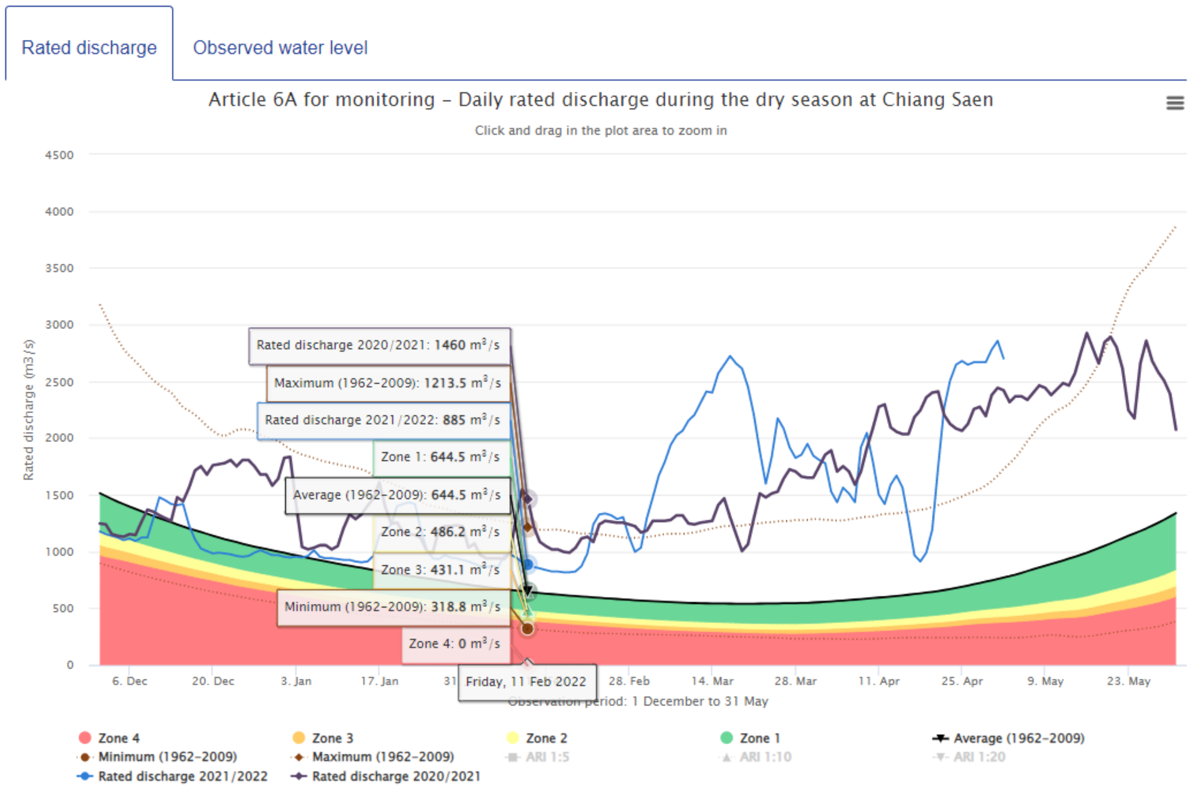
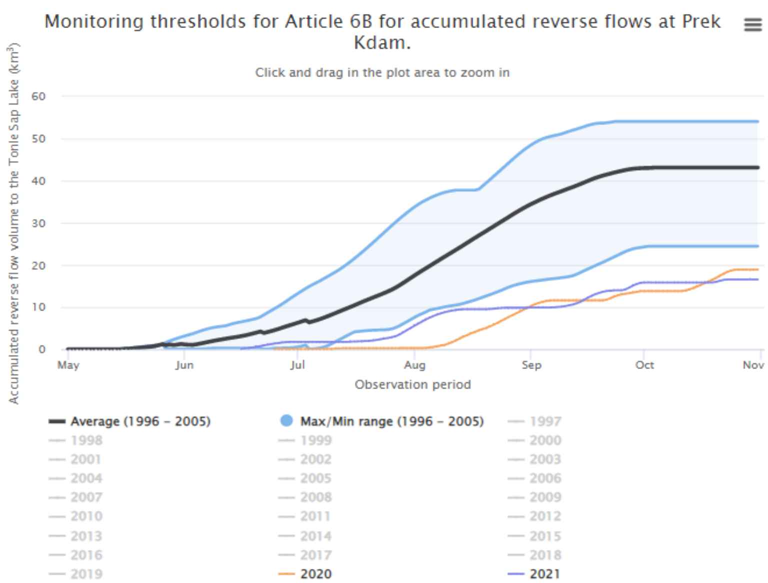


Figure 2. Screenshot of dry season flow against different indices as per Article 6A (Source: MRC, 2022).

Though the above categorisation seems good in principle, it is difficult to implement in practice due to the narrow ranges of water levels and discharges during the dry season. The narrow range leads to low difference in flows and thus they are not physically or statistically significant (MRC, 2018).

2.1.2 Article 6B – Reverse flow monitoring of the Tonle Sap Lake

The reverse flows to the Tonle Sap Lake are monitored using the rules set by Article 6B. The flow framework was developed by MRC based on the Tonle Sap Lake inflow volumes observed at Prek Kdam station between May and September. The accumulated reverse flow volumes at Prek Kdam are determined by combining the available data at Kampong Luong in Tonle Sap and Phnom Penh Port in Tonle Sap River between 1996 and 2005. When the reverse flow to Tonle Sap Lake at Prek Kdam at a given time lies outside of the maximum or minimum thresholds, the hydrological condition is flagged as 'unstable' and mitigation measures need to be undertaken along with investigation of probable causes (MRC, 6B, 2022). The screenshot of the MRC webpage visualising Article 6B for monitoring purposes at the Tonle Sap Lake is shown in Figure 3.



Accumulated reverse flow values

Move over the chart to see its data values below.

Accumulated reverse flow volume (km^3) on 27 Oct	
Average (1996 - 2005)	43.13
Max/Min range (1996 - 2005)	24.46 - 54.05
2020	18.89
2021	16.56

Figure 3. Image showing visualisation of Article 6B for flow monitoring of Tonle Sap (Source: MRC, 2022).

As many hydropower dams have come online across the Mekong, the opportunities for managing the wet season flows are limited and the only options to do so are to issue warnings of extreme conditions (MRC, 2018).

2.1.3 Article 6C – Flow monitoring during the wet season

Similar to the flow monitoring in the dry season, the flows in flood (wet) season are monitored using the framework set by Article 6C. The peak daily observed water levels and derived discharge from 1 July to 31 October are compared against various ARI levels of observed flows at selected hydrological stations. As in Article 6A, there are four classifications based on the daily water level, which are enlisted in Table 2.

Table 2. Flow monitoring during the dry season as per Article 6C (MRC, 2018).

Zone	If the daily flow is…	Hydrological condition	Action
Zone 1 (green)	Above ARI 1:2	Normal	No need for action
Zone 2 (yellow)	Between ARI 1:2 and ARI 1:10	Stable	Need for caution
Zone 3 (orange)	Between ARI 1:10 and ARI 1:20	Unstable	Need to be on alert. Identify probable causes and mitigation measures
Zone 4 (red)	Below ARI 1:20	Severe	Implementation of mitigating measures

The Article 6C, which compares daily rated discharge against various thresholds during the flood (wet) season is illustrated in Figure 4.

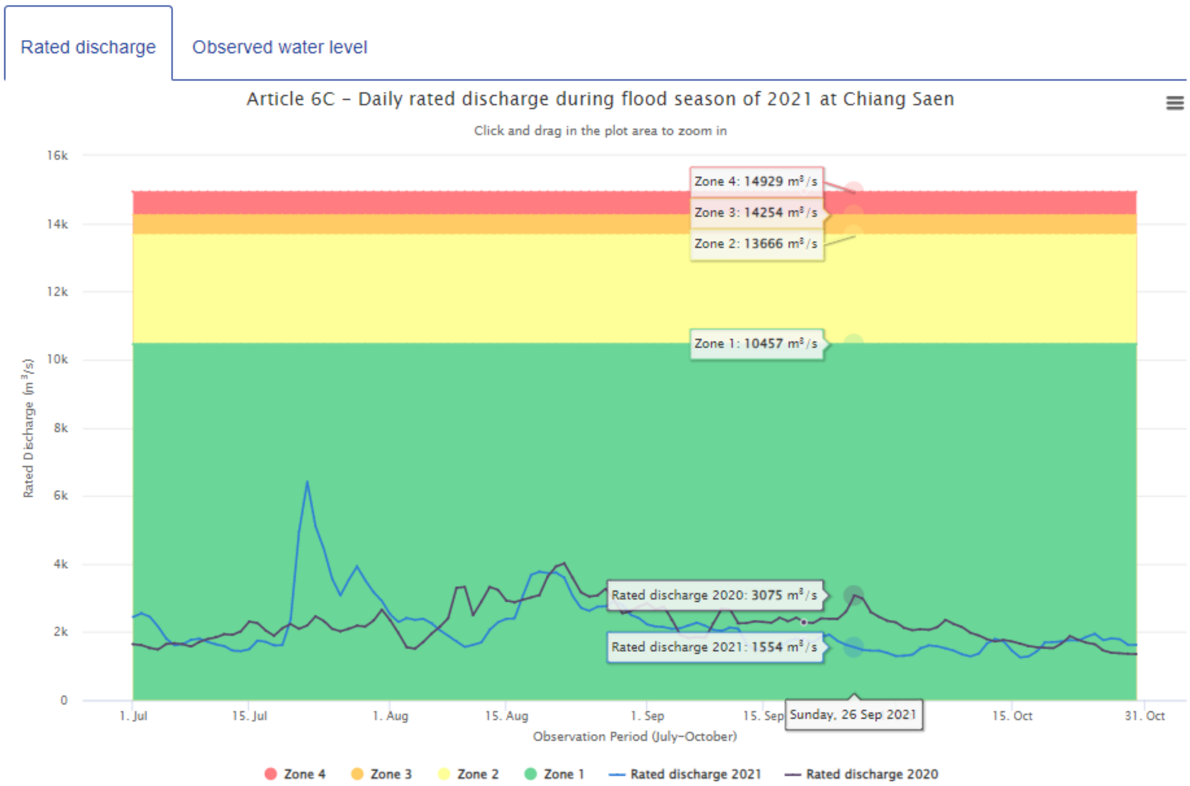


Figure 4. Image showing the visualisation of Article 6C for flood monitoring at station Chiang Saen (Source: MRC, 2022).

The flood season flows are monitored at nine hydrological stations selected based on the hydro-geographic analysis. Two additional stations (Prek Kdam and Kampong Luong) were selected to track the reverse flows of the Tonle Sap Lake.

2.2 Other flow monitoring frameworks of MRC

The MRC also monitors the water level during the dry season and conducts flood forecasting during the wet season. Hydro-meteorological data from 138 stations are collected to forecast water levels at 22 selected stations along the Mekong (MRC, flood forecasting, 2022b). This water level information is published in dedicated flood forecasting websites and daily bulletins and shared with member countries and the public. During the low flow season (December to May), the weekly water level information is used to forecast weekly and monthly droughts, which is disseminated to various stakeholders and the public. A **recent update of combined Mekong River monitoring and forecasting** containing current status on the mainstream, river forecasting in the next five-day, flash flood guidance, drought forecasting and rainfall observation(Figure 5) provides a centralised hydrological condition of the Mekong mainstream and unified communication message to various stakeholders.

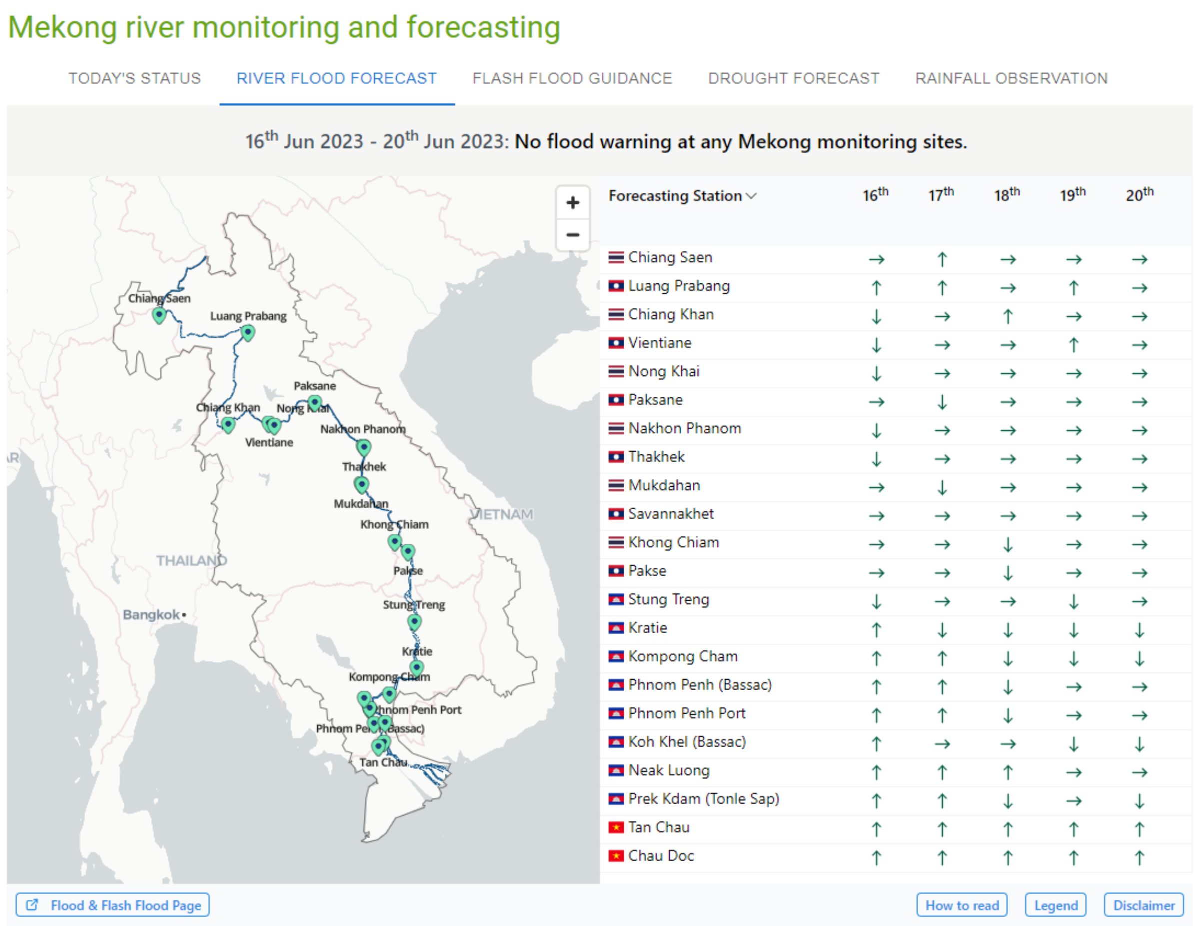


Figure 5. Updated combined Mekong River monitoring and forecasting containing current status on the mainstream, river forecasting in the next five-day, flash flood guidance, drought forecasting and rainfall observation.

Furthermore, more **specific webpages of river monitoring** show hydrographs of daily water levels prepared and compared to long-term averages to inform anomalies, if any. For example, Mekong's near real-time water levels at different stations during the dry season are compared with the long-term average water levels and visualised on the main web page as in Figure 6. The chart also shows the daily fluctuations in water level.

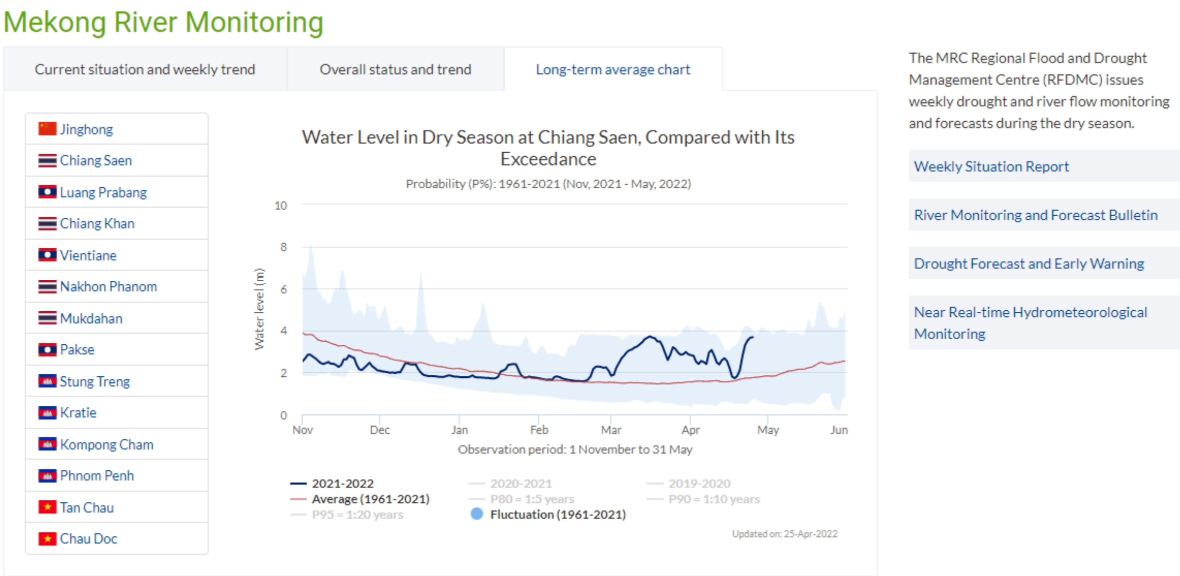


Figure 6. Image showing dry season water level of a Mekong station compared against the long-term average (Source: MRC, 2022).

The monitoring web page of the MRC website has a wide variety of information related to river flow, water quality, flood, drought and fisheries monitoring displayed in map and list views. When a particular station is selected from a list or map, near real-time details such as rainfall, water level etc., can be viewed in chart and table forms. For example, the near real-time hydrometeorological monitoring page shows selected Mekong stations' water level and rainfall trends for different durations. The stations can be selected using map or list views. Time series data for various parameters can also be obtained from the page.

The MRC has also developed another web-based flood and dry period monitoring tool. In the tool, one can select graphs for either flood or dry season listed against selected hydrological stations. If the flood season is selected, the page shows various charts depicting current water levels, water levels over the last week and seven days forecast and observed water levels for the current season at a station. For the first two chart types, the current water level is compared against the flood and alarm levels. Figure 7 shows a snapshot of the web tool illustrating the schematic cross section of a river station with the current water level along with flood and alarm levels.

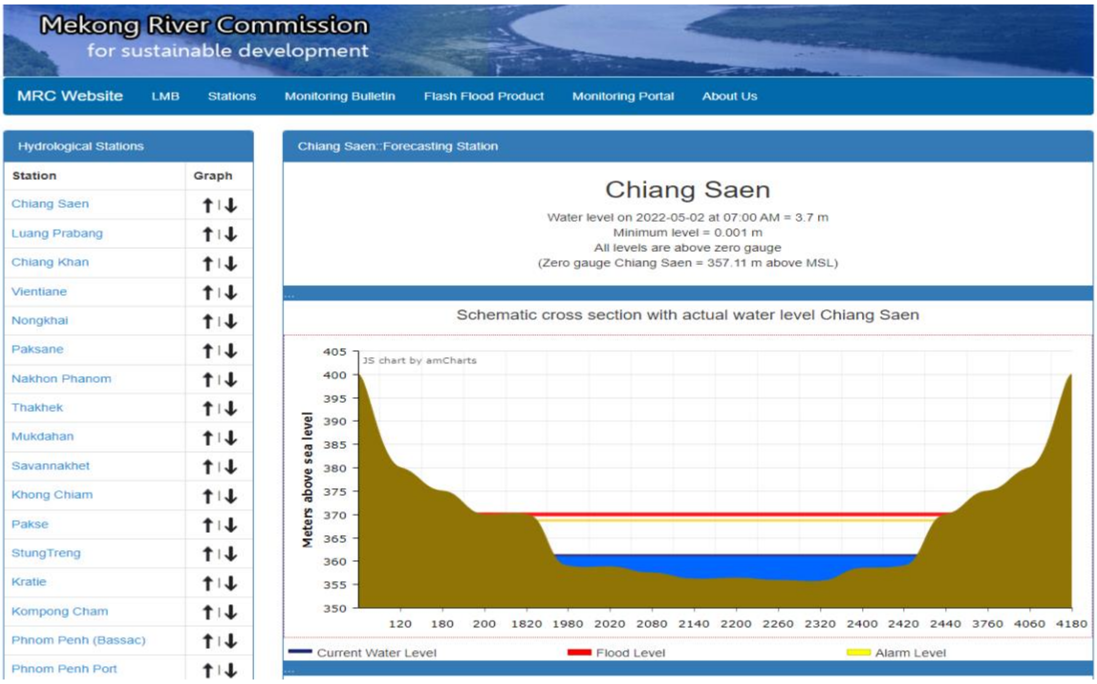
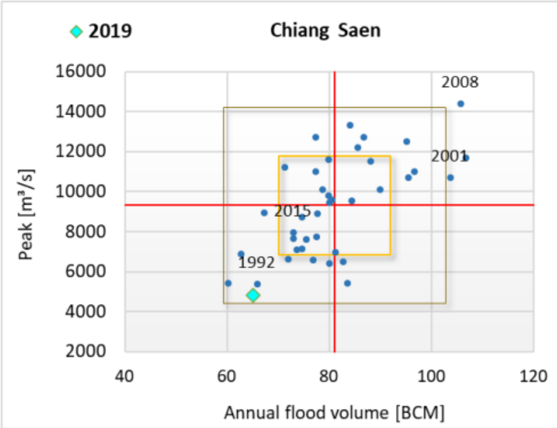


Figure 7. Image showing the current water level along with flood and alarm levels at Chiang Saen Station (Source: MRC, 2022).

The water level at a station for the current season is also compared against the observed maximum, minimum and average values along with selected seasons of previous years for a particular station. This is a handy comparison to see whether the trend is normal or unusual and helpful to identify the time since major changes in water level patterns occurred.

The **Annual Mekong Hydrology, Flood and Drought Report** contains a comprehensive overview of hydrological conditions, flood events, and drought occurrences in the Mekong River Basin. While specific content may vary, the report generally includes the following information:

- Hydrological Analysis: analyses water flow patterns and onset and offset of low/high flows, i.e. historical trends and variations in water levels and discharge.
- Flood Events: provides an assessment of major flood events that occurred during the year. This includes information on the timing, duration, and severity of floods, as well as their impact on communities, infrastructure, and ecosystems.
- Drought Conditions: highlights the occurrence and severity of droughts within the basin. It may include data on rainfall patterns, agricultural impacts, and measures taken to manage drought situations.
- Climate Analysis: includes analyses of climate data (e.g. climate patterns, such as El Niño or La Niña) and its influence on hydrological conditions, flood occurrences, and drought events.
- Future Outlook: Based on the analysis and findings, the report provides an outline of future trends using various source of data and information.
- Country reports reveals national conditions of hydrology, flood and drought and discusses impacts of the disasters and mitigation measures.



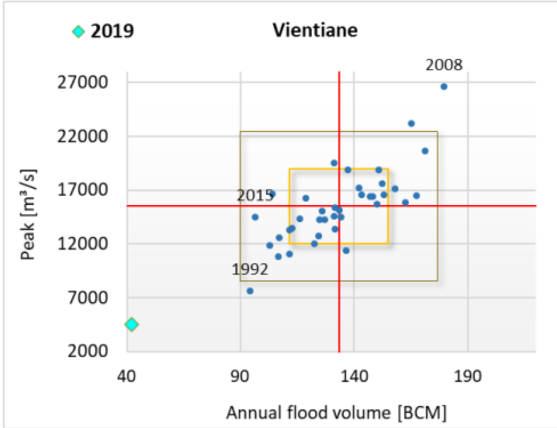


Figure 8. Peak flood and annual flood volume extracted from the Annual Mekong Hydrology, Flood and Drought Report.

3 Guidances and suggestions from the MRC countries

The National Consultation Meetings on the Update of Flow Framework for the Procedures for the Maintenance of Flows on the Mainstream (PMFM) were organised to gather national perspectives on revisiting and identifying new implementable flow thresholds and methodologies for monitoring and managing flow conditions in the Mekong mainstream. These meetings took place in the following locations and dates:

- Lao PDR, Vang Vieng, 2 June 2023
- Viet Nam, Ha Noi, 6 June 2023
- Cambodia, Kampong Cham, 9 June 2023
- Thailand, Bangkok, 16 June 2023

The synthesis of the national meeting outcomes provides valuable input that will inform the ongoing efforts to update the flow thresholds and methodologies. It highlights the broader direction and priorities identified by the Member Countries, contributing to the development of a robust framework for the monitoring and planning purposes.

Cambodia

- Data on the mainstream stations should be verified and updated, especially Chrouy Changvar
- Regular progress report should be provided and communicated with the countries.
- Existing threshold methodology ARI 1:4 for Article 6A planning purposes is preferable for learning-by-doing and practical application.
- A timely alert mechamism should be implemented to send reports to the countries when the flow framework falls into Zone 3 (unstable) and one 4 (severe hydrological condition) according to the PMFM.
- The MRCS, specifically the PD (Planning Division), TD (Technical Division), and OCEO (Office of the Chief Executive Officer), should implement their roles and responsibilities as defined in the PMFM and PMFM Technical Guidelines.
- Reviews and recommendations for improving the implementation of the PMFM should be conducted at the Technical Review Group (TRG) or a similar Expert Group under the provisions outlined in the PMFM and PMFM Technical Guidelines.

- It is suggested to ensure daily time interval for the monitoring purposes and monthly time interval for the planning purposes for complete coverage of the year-round period.
- Hourly water level and discharge at the tidal stations of Tan Chau and Chau Doc should be used for the PMFM implementation.
- The completion of all mainstream hydropower projects would have significant implications for the existing PMFM flow framework.
- The monitoring of adequate reverse flow and other important functions of the Tonle Sap Lake is crucial. Hence, the severity levels/zones of the reverse flow framework should be considered (similar to the monitoring frameworks for Article 6A and 6C). It is important to promptly investigate the causes and take necessary mitigation measures to address any issues related to reverse flow.
- Capacity building is essential for the countries to enhance their ability to implement the flow frameworks effectively.

Lao PDR

- The national meeting suggests that an investigation of the thresholds should be conducted by exploring a more dynamics approach for acceptable limit through the stakeholder engagement; the MRCS can utilise the statistical method, but it should integrate with the modelling approach by considering relevant factors (cascade dam, irrigation pumping head, water supply head, backwater from the sea).
- A baseline is required to reconsider by comparing pre- and post-development; The simulated flow can be used. However, it should be further validated with observed data in which the rating curve is updated to minimise uncertainty.
- The scope of the PMFM is limited to the mainstream, and the roles of the Joint Committee, MRCS and countries are clearly defined in the Technical Guidelines. However, there is a need to address the issue of non-compliance by water infrastructure developers/operators. Furthermore, aligning the PMFM criteria with the hydrology review conducted under the PNPCA is essential.
- The flow framework needs to be revised to align with the emergency action plan for each stage of dam operation along the Mekong Mainstream and the permissible level for navigation.
- Lao PDR has developed flow coordination guidelines based on lessons learned from the PMFM. These guidelines emphasize a more dynamic approach with greater stakeholder involvement in identifying flow thresholds for effective coordination of flows.

Thailand

- An estimate of flow for 1985-2000 is not sufficient due to recent changes in hydrological patterns. It is then recommended to update the period to the present current river condition.
- It is advised to consider monitoring the river condition throughout the year without separating different seasons.
- The current flow frameworks for the dry season use a moving average applied to daily flow values, while the flow framework for the flood season relies on a single value (annual daily peak flows). Adopting a similar approach for deriving thresholds for both the dry and flood seasons is recommended.
- By conducting a scenario comparison and evaluating various aspects of water management, it becomes evident which type of FDC or ARI is more advantageous.

- Collecting long-term datasets of water level and discharge at the tidal stations of Tan Chau and Chau Doc is highly encouraged. This will provide a better understanding of the conditions across the entire basin.
- Updated flow frameworks should consider minimum flow during the flood season and maximum flow during the dry season.
- Rapid water level variation (min-max) should be considered in the review of updated flow frameworks.
- There is a lower peak flow during the flood season compared to previous years. Therefore, ensuring a minimum flow during the flood season would benefit water demand along the Mekong mainstream.

Viet Nam

- The Technical Guideline is still a working document as the flow thresholds for the planning purpose for Article 6A (for the dry season) is not yet agreed. Consensus is therefore recommended to ensure consistent thresholds for maintaining flow in the mainstream.
- It is advisable to assess and analyse the impacts of the hydropower cascade on the establishment of thresholds for the monitoring purposes.
- The data series from 1985-2000 was selected for calculating flow thresholds on the mainstream due to its coverage of extreme periods in the hydrological cycle. If there is a plan to extend the series, it is essential to conduct comprehensive reviews and studies to ensure accuracy and reliability.
- It is recommended to review the calculation results of the threshold at Kratie station, the flow threshold is even lower than the threshold of the Stung Treng station, which is upstream of Kratie station.
- It is recommended to have suitable thresholds for Tan Chau and Chau Doc tidal influence stations. The current thresholds are determined based on the daily average water level, which cannot represent tidal effects.
- It is suggested to consider supporting practical training/capacity building with real situations/conditions on regional/zone basis, for each threshold, how to react/act, early warning should be practice and standard equipment for effective PMFM.

4 Literature review and experience from other rivers

This section comprehensively reviews the various river monitoring types and methods, drawing insights from a literature review of international journal articles and river management organisations in USA, Europe and Australia. This review aims to shed light on the different approaches and techniques employed in river monitoring globally.

Insights gained from these case studies provide valuable lessons and comparative analysis for the river monitoring practices. This comparative approach allows for identifying common challenges, successful strategies, and potential adaptations that can be considered in developing or improving river monitoring systems for the Mekong River.

4.1 Peer-reviewed scientific articles

This section reviews international journal papers and research articles to inform the type and method of river monitoring techniques and frameworks.

The Mann-Kendall (MK) test is one of the common techniques used by researchers to analyse flow trends and other statistical characteristics (Mei et al., 2015; Sauquet et al., 2021; Hannaford and Buys, 2012; Arrieta-Castro et al.,2020; Alifujiang et al., 2021; Guo et al., 2018). Mei et al. (2015) used MK test, grouped frequency tests, and discharge rating curves to test the statistical characteristics of the Yangtze River before and after the Three-Gorges Dam. Sauquet et al. (2021) analysed the trends in flow intermittence using a non-parametric modified MK test. Sauquet et al. (2021) observe that a minimum timespan of 30 years of flow data with less than 5% missing data is ideal for deriving reliable statistics.

Trends in seasonal river flow regimes in the UK was analysed by Hannaford and Buys (2012) using Theil-Sen Slope method and MK test and with suitable indicators. The hydrological indicators selected are mean, Q95, Q90, Q70, Q50 (median), Q30, Q10, Q5. Qn denotes the flow threshold exceeded n% of the time. Q95, (Q5) and Q90 (Q10) are, therefore, indicators of low (high) flow. Each indicator is calculated for each season and year. The authors computed the trend magnitude once the Thiel-Sen slope was fitted to the time series. The trend magnitude for each site was expressed as a percentage of long-term average value of the indicator to enable comparison between sites, especially catchments with large range of mean flow. The authors claim that this approach is comparatively better than a widely used method of expressing a percentage change over the whole data. Figure 9 depicts an example output from the study.

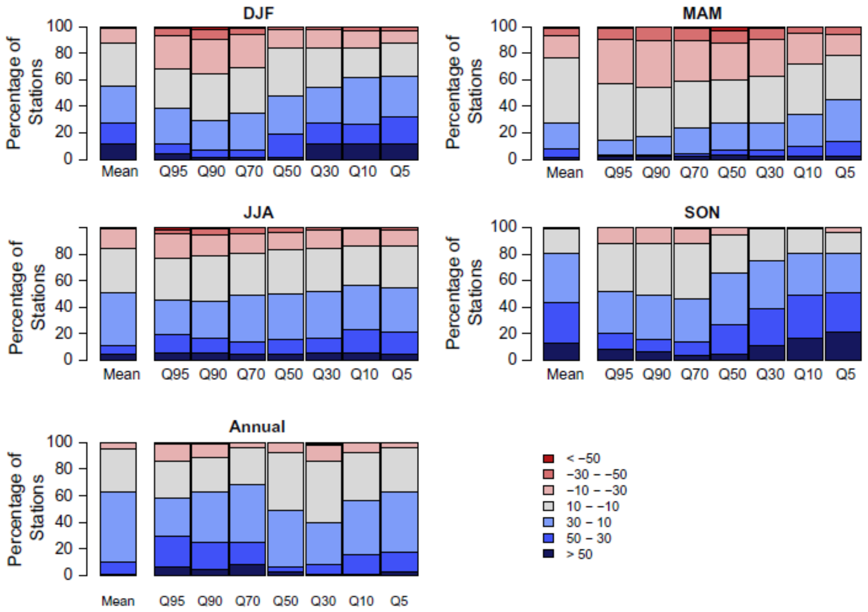


Figure 9. An example of output generated by the study. The boxplots show the proportion of trends in various indicator categories including the mean for various seasons and annual averages (Source: Hannaford and Buys, 2012).

Arrieta-Castro et al. (2020) employed a combination of nonparametric techniques such as the Mann-Kendall (MK), modified MK test (MMK) and the Sen's slope (SS) estimator for analysing the flow trends of Meta River in Columbia. The MK and MMK tests evaluate whether a trend is increasing or decreasing with time. SS is the median of all the pairwise slope values of a set of observed data, that allows the estimation of magnitude. The authors cite that these techniques have been widely used in past studies. One of the advantages of the MK technique is that it is minimally affected by missing and atypical data.

Alifujiang et al. (2021) also used the Mann-Kendall test to detect the temporal trends in annual and seasonal river runoff of the Lake Issyk-Kul basin in Central Asia. They used the MK test along with Innovative Trend Analysis (ITA) to compare the trends. The authors note that the classical trend analysis methods are Sen's slope, regression analysis, and Spearman's Rho and Mann-Kendall (MK) trend test, which search for monotonic trends. The ITA method can be used to identify low, medium and peak trends instead of trend as a whole. The authors claim that the modified MK-ITA test performs better than the above-mentioned traditional methods.

Guo et al. (2018) analysed the trend and change-point of streamflow and sediment discharge of Gongshui River in China for the historical 60 years. Mann-Kendall and Pettitt's test were used for trend and change-point detection. The findings showed insignificant trends of river discharges for all stations, while significant decreasing trend was observed for sediment discharge (Guo et al., 2018).

4.1.1 Mann-Kendall (MK) Test

The Mann-Kendall test analyses data for consistently increasing or decreasing (monotonic) trends in values such as streamflow. It is a rank based, non-parametric (distribution free) test to detect trends in time series hydrological data. However, the test will not work if the data is collected seasonally, for example, only during the summer and winter months. So, the MK test is used when trends occur in different directions in different seasons. The test can also be used when there are missing data. These could be the reason that most of the studies mentioned above used the MK test. However, the test is unsuitable for covariates data, in which other factors could influence the data.

The MK test analyses the sign of the difference between earlier and later data, resulting in a total of n(n-1)/2 pairs of data, where n is the total number of observations (Meals et al., 2011). A trend is confirmed if the Z statistics obtained from the Mann-Kendall test is significantly different from zero. A positive value of Z statistics denotes an increasing trend and vice versa for a negative value.

Though the MK Test is widely used for trend detection in most river studies, the relatively complex methods involved may pose challenges to its implementation as a flow monitoring tool in the Mekong context.

4.1.2 Studies using other methods

Some studies used other flow frameworks, methods, or indicators to monitor river flows. For example, Knoben et al. (2018) used 16 streamflow signatures (patterns) under flow event magnitude, frequency, duration, timing and rate of change to classify hydrological responses to different climatic factors. The high and low flow conditions are covered within the first three categories. The hydrological signatures used by Knoben et al (2018) are listed in Table 3.

Table 3. Hydrological signatures used in this study (Source: Knoben et al., 2018).

Category	Signature	Description
Magnitude	- Mean flow - Q5 - Q95 - Skewness - Baseflow index - High flow discharge	- Normal - 5th percentile of daily flow - 95th percentile of daily flow - Mean divided by median of daily flow - Baseflow fraction of total flow - 90th percentile divided by median flow
Frequency	- No flow frequency - Low flow frequency - High flow frequency	- Normalised average frequency of no flow - Number of days with flow <0.2 * mean - Number of days with flow > 9 *median
Duration	- No flow duration - Low flow duration - High flow duration	- Number of consecutive days with 0 flow - Number of consecutive days < 0.2 * flow - Number of consecutive days > 9 * median
Timing	- Half flow date - Half flow interval	- Fraction of year when 50% flow occurs - Fraction of year in which 25th to 75th percentile flow occurs
Rate of change	- Flow duration curve slope - Rising limb density	- FDC slope between 33rd and 66th percentile in log space - Number of rising limbs divided by time that hydrograph is rising

For each catchment, the authors estimated a signature's value per hydrological year and then calculated average of these yearly values. This process was repeated for all the 16 signatures. Correlation analysis showed that each signature contains some independent information, though not free of duplication. The authors used this method for testing differences between signature values for flows in different representative climates. With this method, the authors arrived at the conclusion that gradual changes in climatic conditions can lead to gradual changes in seasonal streamflow patterns. Also, the method can be used for catchment classification and similarity studies. Using their study approach, the authors showed that the streamflow regimes and signature values in 1103 catchments around the world had strong correlation with local hydroclimate.

Berhanu et al. (2015) attempted to study the spatiotemporal variation in streamflow by means of quantification of flow regime. The authors chose a set of six hydrological indices to characterise magnitude, frequency, duration, timing and rate of change of flow. The flow regime of the gauged streams was defined using the six hydrological indices, which were grouped into three descriptors as in Table 4.

Table 4. Hydrological indicators and their definitions (Source: Berhanu et al., 2015).

Hydrological indicators	Definition
Catchment descriptors	
Flow per catchment unit area	Mean daily discharge divided by the catchment area
Base flow index	Ratio of mean daily discharge to the daily base flow
Flow variability	
Coefficient of Variation	Coefficient of Variation of daily flows
Flashiness index	Flashiness reflects the frequency and rapidity of short-term changes in stream flow
Extent of intermittency	
Mean peak flow day	The mean day of the year for the peak flow occurred
Zero flow day peak	Mean annual number of zero flow days divided by 365

The flow regimes are characterised using the above hydrological indicators and the shape, slope and scale of the flow duration curve (FDC).

Flow signatures are commonly used to study the behaviour of catchments and their hydrological responses. Donnelly et al. (2015) used six flow signatures to evaluate a multi-basin model across Europe. The authors assumed that catchments with similar physiographic characteristics give rise to similar flow signatures. In other words, catchments with similar signatures can be compared using similar hydrological indicators. The hydrological indicators used in this study are listed in Table 5.

Table 5. Hydrological indicators used in the study by Donnelly et al. (2015).

Hydrological indicators	Definition
Long term average river discharge	Mean daily discharge divided by the catchment area
Mean specific discharge	Discharge divided by catchment area
Normalised 95th percentile	High flows divided by catchment area
Normalised 30th percentile	Low flows divided by catchment area
Coefficient of Variation (CV)	Represents dominant flow variability
Hydrograph flashiness	Represents daily flow variability

Hydrological indices or hydrologic metrics or hydrologic signatures are flow descriptors derived from time series discharge data (Mathai and Mujumdar, 2022). The indices give an overall picture of the flow behaviour of the rivers or catchments without having to illustrate the full data. In other words, indices or metrics offer an indirect way to gain insights into the hydrologic processes.

In a study by Mathai and Mujumdar (2022), the authors attempted to differentiate hydrograph limbs using their time irreversibility property and use associated metrics to shed insights into the drivers of streamflow hydrographs in the U.S. The study used rising and falling limb density metrics to analyse the streamflow and correlate them with climate, topography, vegetation, geology and soil.

Rising limb density (RLD) is the ratio of the number of rising limbs and the total time of rising limbs. Falling limb density (FLD) is the ratio of number of falling limbs to the total time of falling limbs. In the Figure 10, RLD is calculated as three divided by sum of ΔT1, ΔT3 and ΔT5. Similarly, FLD is calculated as three divided by sum of ΔT2, ΔT4 and ΔT6. Both FLD and RLD are shape descriptors of the hydro graph without considering the flow magnitude (Mathai and Mujumdar, 2022).

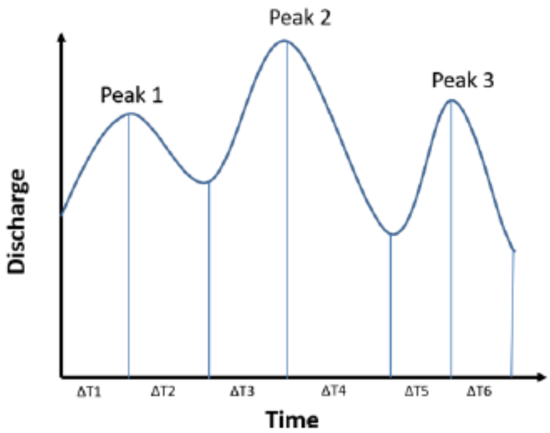


Figure 10. Example for calculating RLD and FLD (Source: Mathai and Mujumdar, 2022; Shamir, 2005).

The study found that the RLD is mainly influenced by elevation, fraction of precipitation falling as snow and depth to bedrock while FLD is characterised by climate factors, mean elevation, and the fraction of precipitation falling as snow.

Descriptors of rising and falling limbs are also mentioned by McMillan (2020) in her review on hydrological signatures and their applications. According to the author, hydrologic signatures range from simple statistical matrices such as mean and quantiles of timeseries to complex indices such as descriptors of rising and falling limbs. The conventional signature classes used by many researchers are magnitude, timing, frequency, duration, and rate of change. Also, statistical-based signatures (flow magnitude, magnitude and duration of annual maxima, timing of annual maxima, frequency, and duration of high and low flow pulses etc.) are generally used for seasonal and longer timescales, while dynamics-based signatures (recession shapes, baseflow index, RLD and FLD, shape of FDC etc.) explain the shapes or trends of the flow series.

Gnann et al. (2021) presents a toolbox in Matlab® named TOSSH (Toolbox for Streamflow Signatures in Hydrology) to calculate hydrologic signatures to provide standardised streamflow dynamics. This toolbox enables users to access more signatures than previous ones with emphasis on hydrological processes rather than statistical descriptions. The signatures or hydrologic indicators covered in the toolbox, which are adopted from the basic set and literature (Addor et al., 2018) are as shown in Table 6.

Table 6. Signatures present in the TOSSH toolbox developed by Gnann et al. (2021).

Components	Signatures/indicators
Magnitude	- Mean flow - 5^{th} and 95^{th} flow percentiles - Mean monthly flow - 7-day minimum flow - Baseflow index (BFI) - Coefficient of variation at flow timestep - Runoff ratio - Streamflow-precipitation elasticity - Slope of distribution of peaks - Low-flow slope of distribution of peaks
Frequency	- High, low and zero flow frequency - snow day ratio
Duration	- High, low and zero flow duration
Timing	- Mean half flow date - Mean half flow interval
Rate of change	- Lag-1 autocorrelation - Slope of FDC - Exponential recession constant - Rising Limb density - FDC low-flow and high-flow

Streamflow-precipitation elasticity is the sensitivity of streamflow to changes in precipitation at the annual time scale. Runoff ratio is the ratio of mean daily discharge to mean daily precipitation.

The authors demonstrate that the spatial variability of baseflow signatures could be caused due to different factors in different regions.

Seemingly similar catchments can behave differently for different events and hence require investigation beyond commonly used hydrological metrics (Fenicia and McDonnell, 2022). Moreover, based on the underlying predominant processes the hydrological signatures that best represent streamflow variability of one catchment may not be fit for another catchment. Fenicia and McDonnell (2022) developed a set of streamflow signatures that define key trends of streamflow spatial variability. According to the authors, the baseflow and quick flow proportions vary between adjacent catchments. Variation also occurs for the time taken for rise in discharges in response to a rainfall event for two catchments with same border and similar baseflow traits.

Based on the visual perceptions of several hydrographs, Fenicia and McDonell (2022) selected four streamflow signatures and they are:

- Streamflow average (mm/yr) denotes the long-term average of streamflow observation
- Baseflow index, which indicates the proportion of baseflow over total flow
- Time-to-peak (hours), which indicates the average duration of rising limbs of the hydrograph
- Relative lag (h), which reflects the gap between two hydrographs. It is the time from beginning of a rising limb to the peak discharge, using hourly resolution streamflow data

They observed that the above four hydrological signatures or indicators could capture streamflow spatial variability. The authors found that the differences in the amount of streamflow observed at various sub-catchments were due to the spatial variability of precipitation. Differences in baseflow and quick flow were due to the variability in lithology. The signature 'time-to-peak' varies due to the differences between topographical and land use. River reach characteristics play a significant role in influencing the relative lag signature.

Berghuijs et al. (2014**)** argue that seasonal water balance has an influence on streamflow variability signatures over a wide range of time scales and flows (low flows to floods). In this study, the authors attempted to develop a similarity framework based on seasonal water balance to cluster catchments that behave similarly. To compare streams and catchments, the authors selected flow duration curve, flood frequency and growth curves, low flow frequency curve and decline curve, base flow index, rising limb density, annual streamflow and interannual variability.

As in many other studies, this study (Berghuijs et al., 2014**)** has also used rising limb density. A higher rising limb density indicates flashy hydrographs. Baseflow is estimated in this study by applying a low-pass filter. Rising limb density and baseflow indicate frequency of fast flows and slow flows, respectively. Landscape properties heavily influence both baseflow index and rising limb density. Therefore, rising limb density could be a good indicator for representing streamflow variability for Mekong Basin.

Flow duration curve (FDC) is another term for the probability of exceedance, in which flow frequency distribution is specified for a particular time step, mostly daily. If used for long term streamflow, the FDC can be used as a probability curve for the estimation of the percent of time that a particular flow will equal or exceed in the future. However, FDC is not a suitable indicator for showing near real-time flow variations as timing of flow is lost during its presentation.

Berghuijs et al. (2014) observed that streamflow variability for short-term, seasonal and longer time scales depends on the combined effects of climate and landscape features. Therefore, it is important to include landscape factors in the similarity framework to make it holistic and universally acceptable.

Coopersmith et al. (2014) used four indices to cluster catchments in the United States into regions of hydroclimatic similarity. They were the precipitation seasonality, aridity index, maximum precipitation day, and maximum runoff date. The indices and their calculation methods are given in Table 7.

Table 7. Hydrological indices used in the study by Coopersmith et al. (2014) to cluster similar catchments.

Hydrological indices	Description
Aridity Index	Sum of mean daily rates of potential evaporation over the 365-day time series divided by sum of mean daily precipitation rates over the same period. The index demonstrates the competition between energy available and water available annually
Seasonality Index	Shows whether precipitation is uniform or periodic by measuring within-year variance of precipitation. It helps to differentiate regions with high seasonal variation of precipitation from those with uniform precipitation
Day of Peak Precipitation	Shows whether precipitation is in-phase or out-of-phase with respect to potential evapotranspiration
Day of Peak Runoff	Depicts the role of catchment storage and release processes. Also shows the transformation happening to runoff at and below land surface including groundwater processes

The significance of these hydroclimatic indices were tested using statistical methods in the study. Hence, this involves some calculations and the suitability for inclusion in the Mekong flow monitoring framework needs to be assessed.

There are some papers which studied impacts of dams or human interventions on river flow regimes. These studies (Zhang et al., 2017; Gao et al., 2009) used various flow regime metrics to investigate the impacts of dams on the downstream flows. These indicators are often classified as Indicators of Hydrological Alteration (IHA). The IHA assess the degree of hydrologic alteration caused by human interventions and involves comparison of flow regimes before and after the intervention periods. Some of the indicators considered by these studies are given in the Table 8. In addition to the indicators listed in the table, Gao et al. (2009) used minimum and maximum flows for 1, 3, 7, 30 and 90 days as well.

Table 8. Indicators of hydrologic alteration used in Zhang et al. (2017) and Gao et al. (2009).

Groups	Flow regimes	Hydrologic indicators
Magnitude	- Average flow	- Annual average daily runoff - Mean daily runoff in each month - Baseflow index
Variability and Frequency	- Average flow - Low flow - High flow	- Coefficient of variation of annual average daily runoff - Low flow spell count (<75th, 90th percentiles) - High flow spell count (>10th, 25th percentiles)
Duration	- Low flow - High flow	- Low flow spell duration (<75th, 90th percentiles) - High flow spell duration (> 10th, 25th percentiles)
Timing	- Average flow - Low flow - High flow	- Colwell's Constancy of mean daily runoff - Date of annual minimum daily runoff - Date of annual maximum daily runoff
Rate of change	- Average flow	- Mean rate of positive changes in flow from one day to the next (Rise rate) - Mean rate of negative changes in flow from one day to the next (Fall rate)

Gao et al. (2009) used other non-dimensional metrics such as ecodeficit and ecosurplus to quantify the deficit and surplus flows caused due to evaluate the impacts caused by streamflow regulations. The ecodeficit and ecosurplus are calculated based on either a period of record Flow Duration Curve (FDC) or median annual FDC. As in Figure 11, ecodeficit is depicted by the area below the unregulated median FDC and above the regulated FDC. Similarly, ecosurplus is the area below the regulated FDC and above unregulated FDC. Furthermore, ecodeficit/ecosurplus is defined as the ratio of ecodeficit/ecosurplus area to the total area under the unregulated FDC. Thus, eco-flow statistics can be used to estimate the unavailable or surplus water caused due to flow regulation, using FDCs of flows before and after regulation. This can be undertaken using monthly, seasonal, or annual FDC to see the impacts for every month, season and year before and after regulation such as upstream dams. This method could be particularly suitable and applicable in the case of Mekong, where there are regulating structures at multiple points. For example, the ecodeficit and ecosurplus for a drought year FDC can be compared with that of a normal low flow year FDC to understand the impacts of regulation on the flows.

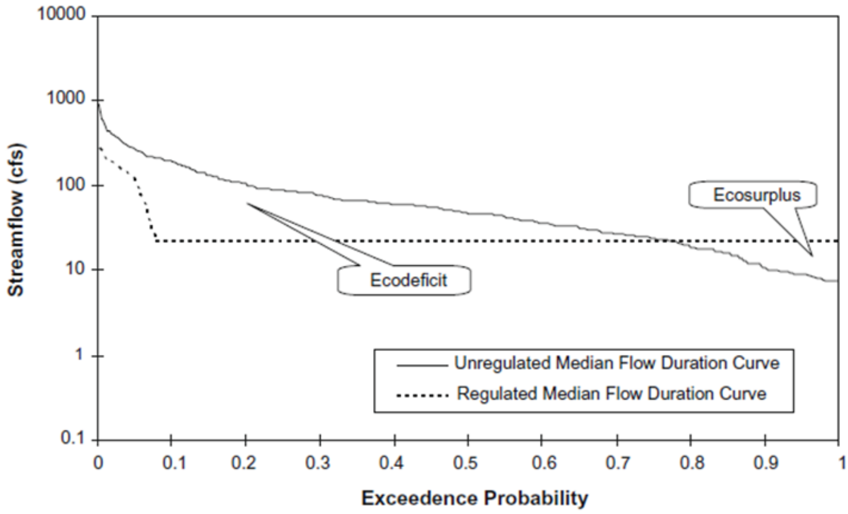


Figure 11. Illustration of the concept of eco-deficit and eco-surplus using FDC (Source: Gao et al., 2009).

In addition to the international journal papers, some technical reports also mentioned about the need for flow monitoring tools and frameworks. Stein et al. (2021) endeavoured to develop a robust river ecosystem framework named California Environmental Flows Framework (CEFF) to use by various stakeholders in the state.

The CEFF was formed as a result of a collaborative effort by researchers, scientists and agency personnel in California to create a robust framework for protecting river ecosystems, which would be flexible to use by various stakeholders in the state. The aim was to inform a holistic understanding of the flows in rivers that were needed to sustain the physical, chemical, and biological functions of the rivers. Another major objective was to improve the coordination and data sharing among water managers and other stakeholders.

According to the CEFF, the functional flows approach can identify the parts of a hydrograph, which are necessary to support various ecosystem functions and health (Stein et al., 2021). For example, Figure 12 illustrates an idealised annual hydrograph associated with important physical processes and species needs that are supported by functional flows.

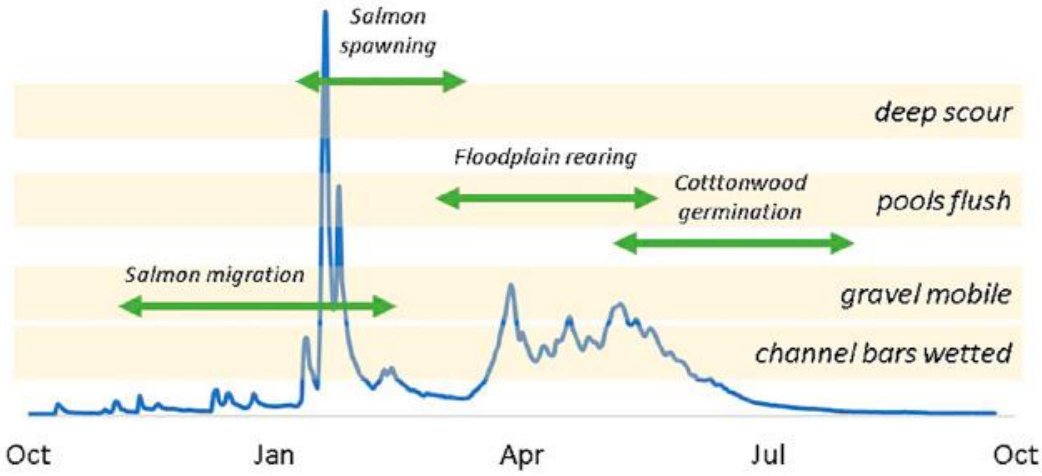


Figure 12. An idealised annual hydrograph as per the CEFF (Source: Stein et al., 2021).

Most of the Californian rivers have five functional flow components that are vital for the ecosystem health and sustain human and other native species needs (Stein et al., 2021). The functional flow components are depicted in Figure 13.

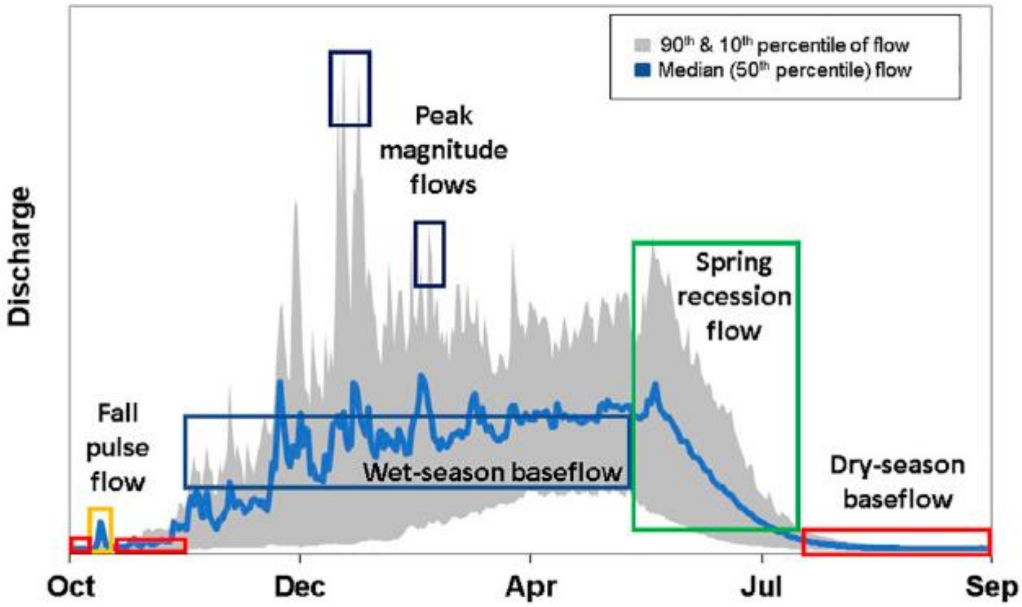


Figure 13. A representative hydrograph showing the five flow components for California (Source: Stein et al., 2021).

Flow metrics such as magnitude, timing and duration can represent the flow components as shown in Table 9. The table shows the example based on the CEFF process for Californian rivers.

Table 9. Flow metrics used in CEFF (Source: Stein et al., 2021).

Functional flow component	Flow metric	Environmental flow recommendation examples
Fall pulse flow	- Magnitude - Timing - Duration	- 62 (30 – 180) cfs - Oct 20 (Oct 7 – Oct 28) - 3 (2 -7) days
Wet season baseflows	- Magnitude - Timing - Duration	- 324 (260 – 410) cfs - Nov 13 (Nov 3 – Nov 30) - 168 (145 – 184) days
Peak flow	- 5-year peak flow magnitude - 5-year peak flow duration - 5-year peak flow frequency	- (3000-4800) cfs - 3 (1-6) days - 1 (1-3) event(s)
Spring recession flows	- Magnitude - Timing - Duration - Rate of change	- 520 (300-980) cfs - Apr 28 (Apr 6 – May 14) - 50 (36-66) days - 6 (3 – 10) % decline per day
Dry season base flows	- Baseflow - Start timing - Duration	- 22-23 cfs - June 20 (June 5- July 7) - 151 (121-183) days

Though the CEFF has been developed, it is not yet implemented and hence an implementation workplan is being developed currently.

A plugin called 'River Analysis Package' is available within the commonly used hydrologic modelling tool eWater Source® (2022). The package contains a time series analysis module which has listed some of the time-series metrics used for river flow analysis and they are:

- General statistics – Mean, median, Q90, Q10, Skew, Coefficient of Variation
- High and low flow spell analysis – estimate statistics based on above and below threshold levels
- Colwell's statistics – provides a measure of seasonal predictability of phenomena
- Rates of rise and fall
- Base flow analysis
- Partial series flood frequency
- Annual series flood frequency

The module also gives a graphical display of alternative metrics which are dynamic, and they are:

- Annual, seasonal and monthly time series display
- Flow duration curves – whole period, annual, seasonal and monthly
- Partial and annual flood frequency curves
- Base flow component of flows

Among the above metrics, spell analysis plots help in visualising the duration and frequency of flows above or below a threshold and are relatively easy to understand. An example of high spell plot by Ladson (2022) for a creek in Victoria, Australia is illustrated below. Figure 14 shows the high spells, in which flows are more than 10 ML/d, from 1962 to 2015 for every month. It can be inferred from the plot that high spells above 10 ML/d generally occur between June and December every year, though there are variations in some years. Also, around 2000 and after, the high spells are scattered across the months of June to December, showing less continuity. Similar inferences could be made from low spell plots as well, which help to inform the stakeholders about the discrepancies in flows between years.

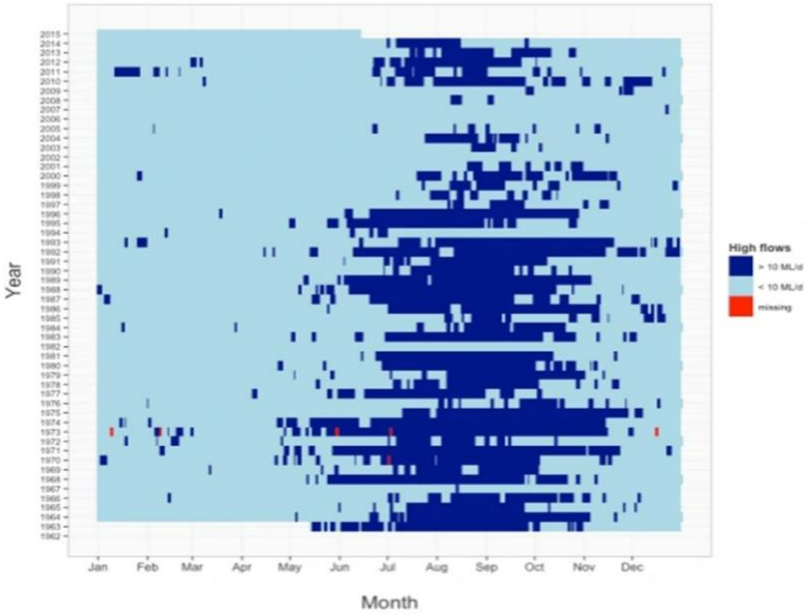


Figure 14. Example of a high spell plot (Source: Ladson, 2022)

High and low spell plots can be adopted as flow monitoring tools by MRC due to their ability to demonstrate temporal variation of flows within and between years a simple manner.

4.1.3 Indicators of Hydrologic Alteration (IHA)

This software program assesses the 67 ecologically significant statistics derived from daily hydrological data. As an example, the time and maximum flow of annual flood or low flows can be calculated using the IHA. Using comparative analysis, the change in flow patterns for a particular river or lake due to any developments can be described statistically. Out of the 67 parameters, there are 33 IHA parameters and 34 Environmental Flow Component (EFC) parameters.

Hydrologic parameters

The IHA includes 33 hydrologic parameters that characterise the intra- and inter-annual variation in flows and those characteristics are mainly classified into five different parameter groups as given in Table 10.

Table 10. The flow regime characteristics according to IHA classification and the parameters

IHA Parameter Group	Hydrologic Parameters	Ecosystem Influences
Magnitude of monthly water conditions	- Mean or median value for each calendar month	- Soil moisture availability for plants - Reliability of water supplies for terrestrial animals - Influences water temperature, oxygen levels
Magnitude and duration of annual extreme conditions	- Annual minima, 1-day mean - Annual minima, 3-day means - Annual minima, 7-day means - Annual minima, 30-day means - Annual minima, 90-day means	- Structuring of river channel morphology and physical habitat conditions - Soil moisture stress in plants - Duration of stressful conditions such as low oxygen

IHA Parameter Group	Hydrologic Parameters	Ecosystem Influences
	- Annual maxima, 1-day mean - Annual maxima, 3-day means - Annual maxima, 7-day means - Annual maxima, 30-day means - Annual maxima, 90-day means - Number of zero-flow days - Base flow index: 7-day minimum flow/mean flow for the year	
Timing of annual extreme water conditions	- Julian date of each annual 1-day maximum - Julian date of each annual 1-day minimum	- Predictability/avoid ability of stress for organisms
Frequency and duration of high and low pulses	- Number of low pulses within each water year - Mean or median duration of low pulses (days) - Number of high pulses within each water year - Mean or median duration of high pulses (days)	- Frequency and magnitude of soil moisture stress
Rate and frequency of water condition changes	- Rise rates: mean or median of all positive differences between consecutive daily values - Fall rates: mean or median of all negative differences between consecutive daily values - Number of reversals	- Drought stress

A day is classified as a pulse if it exceeds a specified threshold. High pulses are those flows greater than the 75th percentile daily flow, while low pulses are those lower than the 25th percentile flow.

Environmental Flow Components (EFC)

A summary of Environmental Flow Component (EFC) parameters is given in the Table 11.

Table 11. Environmental Flow Component (EFC) parameters

Environmental Flow Component type	Hydrologic Parameters
Monthly low flows	Mean or median values of low flows during each month
Extreme low flows	Frequency of extreme low flows during each season or water year 10th percentile of all low flows Mean or median values of extreme low flow event - Duration - Peak flow (minimum flow during event) - Timing (Julian date)
High flow pulses	Frequency of high flow pulses during each season or water year

	Mean or median values of high flow pulse event: - Duration (days) - Peak flow (maximum flow during event) - Timing (Julian date) - Rise and fall rates
Small floods	Frequency of small floods during each water year or season Mean or median values of small flood event: - Duration - Peak flow (maximum flow during event) - Timing (Julian date of peak flow) - Rise and fall rates
Large floods	Frequency of large floods during each season or year Mean or median values of large flood event: - Duration (days) - Peak flow (maximum flow during event) - Timing (Julian date of peak flow) - Rise and fall rates

The IHA tool classifies each daily flow value into one of five EFCs as shown in Figure 15.

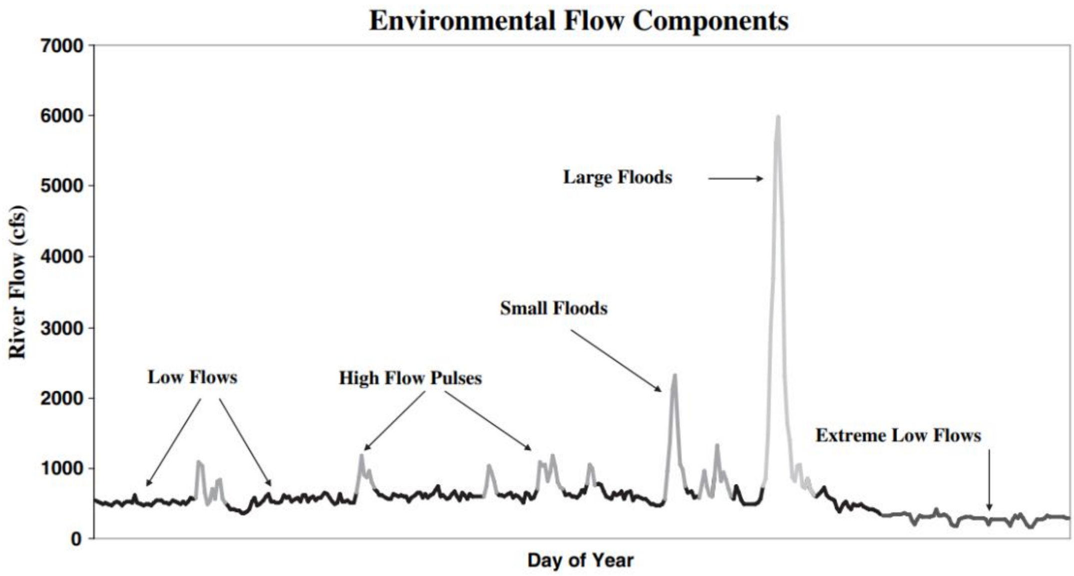


Figure 15. Categorisation of daily flow values according to EFC classification (Source: Mathews and Richter, 2007).

Studies using IHA and its parameters

Pardo-Loaiza et al. (2021) used improvised IHA to study regulated and complex water resources systems in the Duero River Basin in Spain. They used a set of 12 indicators in this study to analyse natural and altered regimes and they are:

- Magnitude of annual inflows
- Magnitude of monthly inflows

- Normal variability which is the difference between Q_{10} and Q_{90} percentile of inflow
- Extreme variability, which is the difference between maximum and minimum monthly inflows.
- Maximum seasonality
- Minimum seasonality
- Magnitude of normal floods, which is the ratio of 5th percentile of inflows (Q_5) in altered and natural regimes
- Variability of normal floods, which is the ratio of coefficient of variation (CV) of flood flow series greater than Q5
- Flood seasonality
- Magnitude of normal droughts
- Variability of normal droughts
- Drought seasonality

Onwuka et al. (2021) used the selected IHA and Richards-Baker Flashiness Index to characterise flow regimes in three types of channels in southern Florida, USA. The selected hydrologic indices for magnitude were 1-day minimum and 1-day maximum, 90-day minimum and 90-day maximum. For frequency, low pulse and high pulse counts were selected. The upper and low flow thresholds chosen were 75% and 25% of the long-term daily mean flows. Yearly duration of low and high flow pulses were the indicators for duration. For the rate of change indicators, the rate of both positive (rise) and negative (fall) changes in the daily hydrographs during a year were used.

A total of 43 different hydrologic alteration metrics were selected by George et al (2021) to study the hydrologic alteration to fish populations in the U.S. River systems. They are enlisted in Table 12. Hydrologic regime categories and indicators below.

Table 12. Hydrologic regime categories and indicators

Regime category	Definition
Magnitude	- Mean daily flow - Median daily flow - Variability in daily flows (Coefficient of variation in daily flows) - Mean monthly flow for all months, January through December - Mean annual runoff (Mean annual flow divided by catchment area) - Baseflow 1. Seven-day minimum flow divided by mean annual daily flows averaged across all years - Baseflow 2. Mean of ratio of the lowest annual daily flow to the mean annual daily flow times 100 averaged across all years - Mean annual maximum flows divided by catchment area
Duration	- Magnitude of minimum annual flow for 1, 3, 7, 30 and 90 day means - Low pulse duration - Number of zero flow days - Annual maxima of 1-, 3-, 7-, 30- and 90-day means of daily discharge - High flow pulse duration
Frequency	- Low flood pulse count

	- High flood pulse count - Flood frequency - mean number of high flow events per year using 3 times median annual flow - Flood frequency – mean number of high flow events per year using 7 times median annual flow
Timing	- Constancy - Predictability of flow
Rate of change of flow	- Rise rate – mean rate of positive changes in flow from one day to the next - Fall rate – mean rate of negative changes in flow from one day to next - Reversals – number of positive and negative changes in water conditions from one day to the next

In their study method, a low flood pulse count is defined as the number of times the daily flow drops below the 25th percentile which the low pulse threshold. The high pulse threshold is defined as the 75th percentile.

Blythe et al. (2018) used common environmental flow metrics to compare river flows in the northern branch of Rio Grande across different periods. The following metrics as given in Table 13 were used in this study.

Table 13. Environmental flow metrics used in the study

Metric	Indicators
Magnitude	- Mean annual flow (m^3/s) - Median annual 7-day minimum (m^3/s) - Low flow – base flow ratio - Median annual daily maximum (m^3/s) - High flow - base flow ratio
Duration	- Median extreme low flow duration (days) - Flood rate of rise (% of flood magnitude/day) - Flood recession rate (% of flood magnitude/day)
Timing	- Median extreme low flow date - Median peak flood date
Frequency	- Median number of zero flow days/year - Median number of high pulse flows per year

The extreme low flows in this study were calculated as flows less than the 90th exceedance probability from a flow duration curve (FDC), whereas high pulse flows were calculated as flows greater than the 25th exceedance probability flow. The authors classified small floods as high pulse flows with a recurrence interval between 2 and 10 years, whereas large floods as high pulse flows with a recurrence interval greater than 10 years. The researchers (Blythe et al., 2018) calculated the flood duration as the number of consecutive days that the discharge was greater than the threshold of 40th exceedance probability of each annual FDC. The rate of rise was calculated as the difference in discharge between start of flood and peak divided by the number of intervening days. Similarly, the recession rate was calculated by the difference in discharge between the peak and end of flood divided by number of days.

The authors defined low flow – base flow ratio as the median 7-day minimum divided by mean annual flow, whereas the high flow–base flow ratio as the median daily maximum divided by mean annual flow.

Westerberg et al. (2016) used nine flow signatures or indicators to study the uncertainty in hydrological signatures for gauged and ungauged catchments. The nine signatures used in the study are provided in Table 14.

Table 14. Hydrological indicators and their description

Hydrological indicator	Description
Mean flow	Mean flow for the analysis period
Q0.01, Q0.1, Q1, Q5, Q50, Q85, Q95, Q99	Low and high flow exceedance percentiles from the FDC
Base flow index	Ratio of baseflow to total streamflow
Slope of normalised FDC	Slope of the FDC between the 33% and 66% flow exceedance values of streamflow normalised by their means
Overall flow variability	Coefficient of variation in streamflow (standard deviation divided by mean flow)
Low flow variability	Mean of annual minimum flow divided by the median flow
High flow variability	Mean of annual maximum flow divided by the median flow
Flow autocorrelation	Autocorrelation for 1 day

Flow thresholds defined in studies and river organisations

The selection of suitable thresholds is determined by the target water users and operational practices around environmental flow requirements and other demands. In most of the drought studies, the adopted low flow thresholds range between 70% and 95% flow exceedance probability (Cammalleri et al., 2017). The thresholds can be variable or fixed depending on the analysis objective and flow trends of the river and different seasons can have different thresholds (Cammalleri et al., 2017). A daily threshold $Q_{x,t}$ was adopted by Cammalleri et al. (2017) where x is the x^{th} percentile and t the day of the year and was aimed at characterising the natural low-flow regime of the river. The authors used the flow at 95% exceedance probability of the partial FDC as the daily low flow threshold.

Raczynski and Dyer (2022) used the low flow limit as around 30^{th} percentile flow or the highest of the lowest annual flows. And for high-intensity low flows indicating severe hydrological droughts, the threshold selected was around the 10^{th} percentile value. Therefore, the authors suggest that the expected optimal threshold indicating low flows might be somewhere between the 10^{th} and 30^{th} percentiles and the highest value of the low flow threshold may be 50^{th} percentile.

Hoang et al. (2016) calculated monthly and annual statistics to study the changes in Mekong's flow regime. The authors selected 95^{th} and 5^{th} percentiles as the high flow and low flow thresholds respectively.

In their study, Garcia et al. (2017) used Q95 (5^{th} percentile flow), Q75 (25^{th} percentile flow), mean annual 3-day and 10-day minimum discharges (MAM3 and MAM10) and annual minimum monthly discharge (QMNA) at the recurrence interval of 5 years as the low-flow indices. Q95 and Q75 are the flows exceeding 95% and 75% of the time and were derived from the flow duration curve (FDC).

In their study, Gain et al. (2013) used twenty-two 'Range of Variability Approach (RVA)' parameters to calculate the ecological flow threshold of the Lower Brahmaputra Basin. The researchers used 40 years of data ranging from 1956 to 1995 as the observation period for calculating the flow thresholds. Of the twenty-two parameters, twelve represent the mean flow for each calendar month and the remaining parameters are 1-, 3-, 7-, 30- and 90-day minima and maxima. As all the parameters were following normal distribution, they used ±1 standard deviation from the mean as the thresholds for each of the 22 RVA parameters.

Richter et al. (1997) suggested the usage of ±1 or 2 standard deviations, 20th percentile, 80th percentile etc. as the measures of dispersion to set initial flow thresholds for situations which lack extensive ecological information. Standard deviation is used when the parameter is following normal distribution.

River organisations and environmental departments around the world also defined thresholds to classify flows, mainly low flows. The United States Environmental Protection Agency (US EPA) has classified a low flow as the water flow in a river or stream during a continuous long period of dry weather or season. Many U.S. states define low flows as the lowest 7-day average flow (7Q10) once every 10 years. It is computed using the single lowest flow event from each year of record and comparing these flows with historical flows to identify an extreme value such as the lowest 7-day average flow in a ten-year period (7Q10).

According to the European Drought Observatory (EDO), the daily low-flow threshold values are defined as the streamflow values corresponding to the 95th percentile of the flow duration curve ('Q95'). The EDO then implemented Low-Flow Index (LFI) as an indicator for hydrological drought. Based on the defined LFI, a hydrological drought is defined as a period of consecutive days with daily flows lower than the Q95. Indicators of hydrological drought are based on threshold approaches in order to quantify the water deficit in rivers and reservoirs. According to the EDO, LFI can be used for near real-time monitoring of hydrological droughts and represented in the form of maps and graphs.

The Murray Darling Basin Authority (MDBA) in Australia define low flows as the flows which fall under the 5th percentile of all daily flows in the unimpacted period or 'natural flow' period, or 10% of the mean unimpacted flow volume.

For Hunter River in Australia, low flow is defined as daily flows below the 20th percentile flow and very low flow as daily flows below the 5th percentile flow.

The Department of Environment and Primary Industries (2013) of the Government of Victoria in Australia recommends the use of different thresholds for different period of the year. For example, a different low and high flow thresholds are recommended for winter and winter periods in this strategy.

Change point detection - Pettitt's test

The non-parametric Pettitt test is commonly used to determine the transition year in which a change in hydrological records of a station may have occurred. The method counts the number of times that a member of the first sample exceeds a member of the second sample using a test statistic and corresponding probability.

There are many studies which use Pettitt's test to identify the year of change in hydrological patterns in their data. In one of the studies, Guo et al. (2018) used Pettitt method with a statistical significance level of 5% to determine the year in which abrupt transition in hydrological records of the Gongshui

River might have occurred. The authors used the Pettitt method to identify the transition year of annual sediment discharge, precipitation and streamflow. The study results showed that change-points in sediment discharge data could be detected for all stations except one, while no transition points could be found for precipitation and streamflow at any station.

4.2 Flow monitoring by river organisations and environmental agencies

In addition to the literature review, this section explores the experiences and practices of river monitoring in other major river systems worldwide. A broader perspective on river monitoring can be achieved by examining examples such as the Murray-Darling River in Australia, the Nile River in Africa, and other prominent river basins in USA, Canada and Euroup.

4.2.1 Murray – Darling Basin

There are many international river organisations and authorities which are entrusted with the task of river management. As a part of river management, they use various flow frameworks and monitoring tools. This section aims to review the flow monitoring tools and frameworks developed by other river organisations to inform relevant flow monitoring frameworks and methods.

The Murray-Darling Basin is a system of interconnected rivers and lakes spanning a large area of south-eastern Australia. The Basin covers an area of more than a million square kilometres and provides water to 2.3 million people, sustain a large ecosystem, and supply irrigation water to thousands of farms (MDBA, 2022). The Basin is collectively managed by various state governments and the Murray-Darling Basin Authority (MDBA). The MDBA oversees the overall basin water management, including the health of the Basin as a whole. MDBA is entrusted with regular determination of water in the River Murray system and informing the state governments about their share. The MDBA also updates the daily information about water flow rates, release rates and heights across the Murray River system along with weekly forecasts of storage levels, flows and salinity.

The parameters such as water level, flow, volume, release, water temperature, salinity and rainfall for selected stations (river gauge, storage or weir) along the Murray River system are monitored in near real-time on an hourly interval and can be viewed in MDBA's dedicated website (www.riverdata.mdba.gov.au). The data are obtained by a network of remote hydrometric monitoring stations, which records and sends the data via telemetry.

The parameters can be viewed as a system, list and map forms. The system view of River Murray system is illustrated in Figure 16 below. The system view shows the river flow rates, water levels and release rates across the River Murray system and its tributaries.

Detailed information such as water level, flow, rainfall, water temperature and salinity are available for each of the points/stations on a near real-time basis. Historical data is also available for download for each station. List and map views of the system are also available. The near real-time data is updated on an hourly basis. At some sites, forecast data about water level and flow for the next one week is also displayed.

The up-to-date flow information at key locations along the Murray River system are available from the Australian Bureau of Meteorology (BoM) websites and riparian states. The flow and water level information are used to assess the river and ecosystem health. The water allocated for each end use and extraction per the basin plan are also evaluated and published in weekly reports.

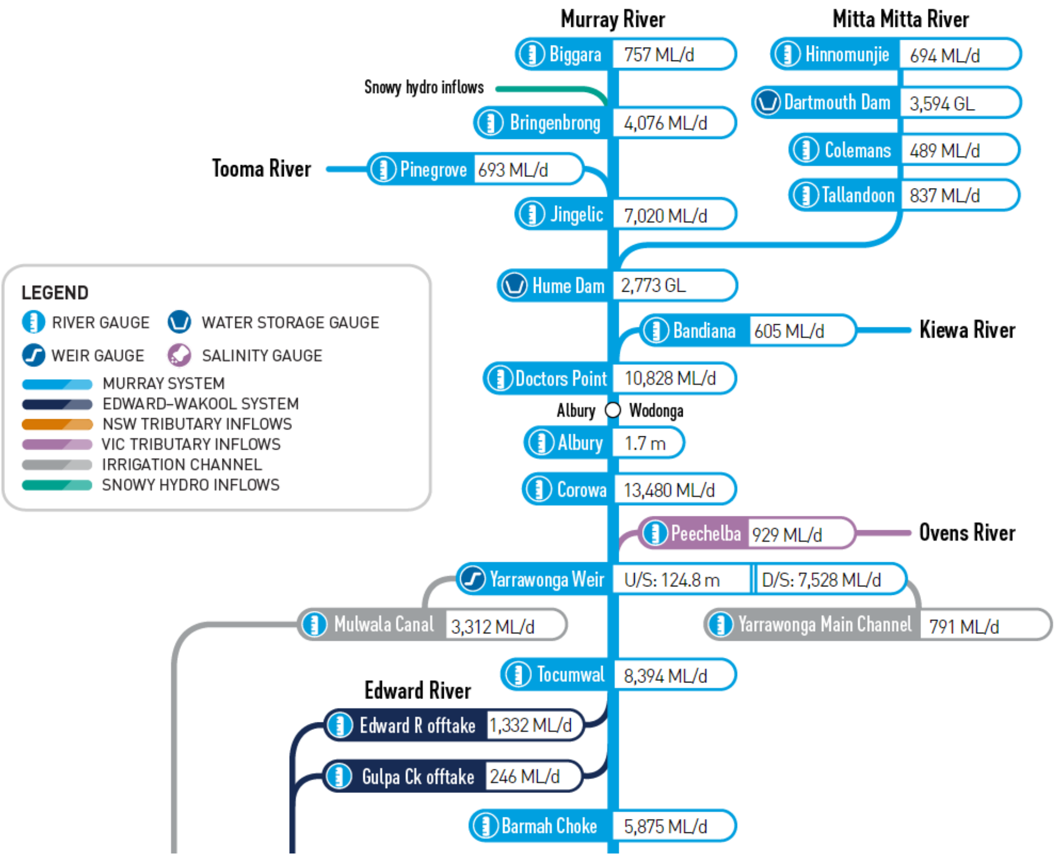


Figure 16. System view showing the water flow rate at various stations of River Murray System.

However, the comparison of current flows and levels in the river with historical flows and levels are not demonstrated in the above websites and charts. The MDBA uses two satellites by the European Space Agency's Sentinel 2A and 2B satellites to monitor water flows across the basin to identify anomalies (MDBA, 2020). Using satellite imagery along with gauge flow data helps the MDBA finds unexpected or unusual flow changes.

Lately, the MDBA and the Bureau of Meteorology (BoM Australia) have updated their water information portal, which provides clear insights into storage, river gauges and rainfall status of the Murray Darling

Basin. The screenshot of the MDBA portal is shown as in Figure 17, which shows the overview of the basin. The user can select a catchment to see the related storage, river gauges or weather information.

Within each catchment, the overview tab provides a snapshot of the river system with a flow diagram showing near real-time flow and storage information. The 'Water availability' tab shows the combined water storage and summary statistics related to the catchment. The water allocations table shows how the water is shared between different users. The 'Storage' tab provides the current and comparative storage status of all the major storages, weirs and locks, and other storages that supply water for urban areas, hydroelectricity and other purposes. The 'River gauges' tab shows key gauges with information regarding the latest and past flows, level and water quality (salinity, temperature, pH, turbidity). The market prices of water per unit volume for a catchment is provided under the 'Water trade' tab.

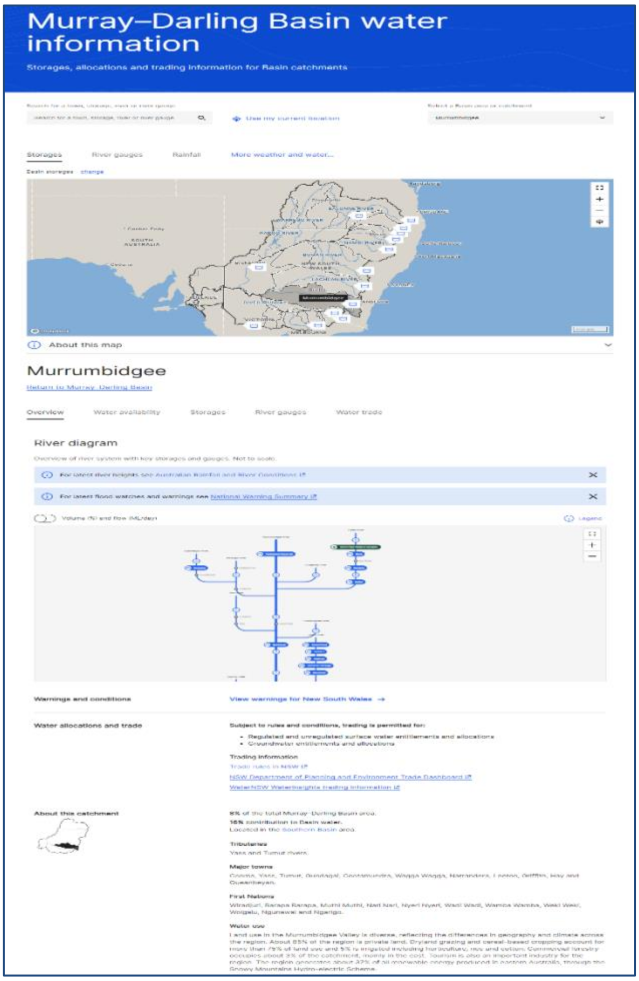


Figure 17. The updated Murray-Darling Basin water information portal (Source: MDBA and BoM, 2022).

The latest water information portal by MDBA is beneficial for the general public to view the latest and past water information in a detailed fashion without navigating to many other pages. The overview river diagram with volume and flow details in a sub-catchment could be adopted by the MRC.

4.2.2 Nile River Basin

The Nile River Basin covers more than three million square kilometres spread across 11 countries, making it one of the most shared basins in the world. The Nile Basin supports livelihoods of over 250 million people. Several programmes have been taken place for water management among the Nile countries (Digna et al., 2017). However, due to varied reasons, including the absence of regional institutions to coordinate water management, there is no comprehensive and cooperative water management programme involving all riparian countries (Digna et al., 2017). The Nile Basin Initiative (NBI) was started by the riparian countries in 1999 to ensure basin-wide cooperation and identify and implement infrastructural projects (Digna et al., 2017).

The core functions of the NBI are to build cooperation amongst the Nile countries, manage water resources using analytic tools and shared information system and to identify development opportunities such as power generation and agricultural production. The flow monitoring and forecasting by the NBI are used for operational decision making in the Nile. The NBI produces drought monitoring and forecasting bulletins as a part of basin flow monitoring and forecasting system. The parameters such as rainfall, temperature, soil moisture and vegetation status are monitored and compared with that of previous years to inform deviations from long term averages. Meteorological, hydrological and agricultural drought are regularly monitored using Standardised Precipitation Index (SPI), Soil Water Index (SWI) and Normalised Difference Vegetation Index (NDVI) (NBI, 2021). The averaged year for comparison is calculated from the recorded observations since 2000. Monthly rainfall deviation maps are produced to visualise the anomalies as compared to historical values.

The water levels in major lakes within the Nile Basin indicate the river's health; hence, lake height variations are estimated from satellite altimetry data. These estimations are compared with a 29 year mean level derived from earlier satellite data (NBI, 2021). However, the long-term average data are only available for some of the lakes.

The Nile River is subjected to high seasonal and inter-annual variability and is vulnerable to droughts and floods. Though several river modelling exercises were carried out based on the Nile, there is a lack of a user-friendly interactive web tool to demonstrate the near real-time hydrometeorological monitoring of the Nile at various reaches.

The forecast and monitoring page of Nile Basin Initiative (http://ikp.nilebasin.org/en/flood-monitoring) has options for flood forecast and early warning system, river forecast system and drought forecast and early warning system for the Eastern Nile Flood Prone and river locations as in Figure 18. In the map view, users can select a station and look for the river flow threshold values to see whether the flow is above or below the thresholds. However, the details for many of the stations are not updated recently and information regarding stations are not comprehensive.

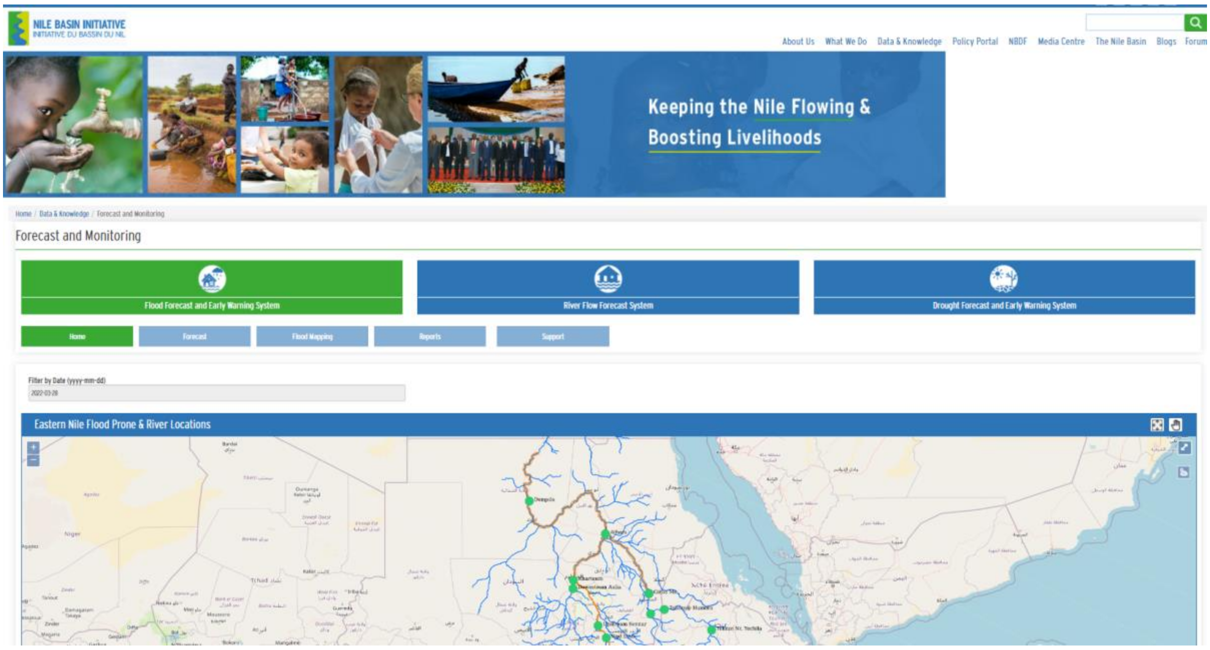


Figure 18. Dashboard showing flood and drought forecasting and monitoring for the Nile River Basin (Source: NBI, 2022).

4.2.3 U. S. Geological Survey (USGS) National Water Dashboard

This review has found that the web-based tool developed by USGS has comprehensive and intuitive dashboard illustrating near real time streamflow rates, surface water, groundwater and spring water levels, water quality and atmospheric conditions. The National Water Dashboard shows the surface water and groundwater status of all major stations across the U.S. as in Figure 19 below. The streamflow tab shows the status as high flow, low flow and not flowing for various stations. As an example of the utility of this dashboard, when ‘Low flow’ is selected from a list under the Streamflow, the station summary gives a table showing ‘Day-of-Year’ status of the stations with low flows (Figure 20). The ‘Day-of-Year’ status shows the percentage of stations with below normal, much below normal and all-time low flows for any day of the year. Similarly, High flow shows stations with all-time high, much above normal and above normal for that day of the year. The Streamflow item from the list shows the summary of high flow and low flow status of all stations.

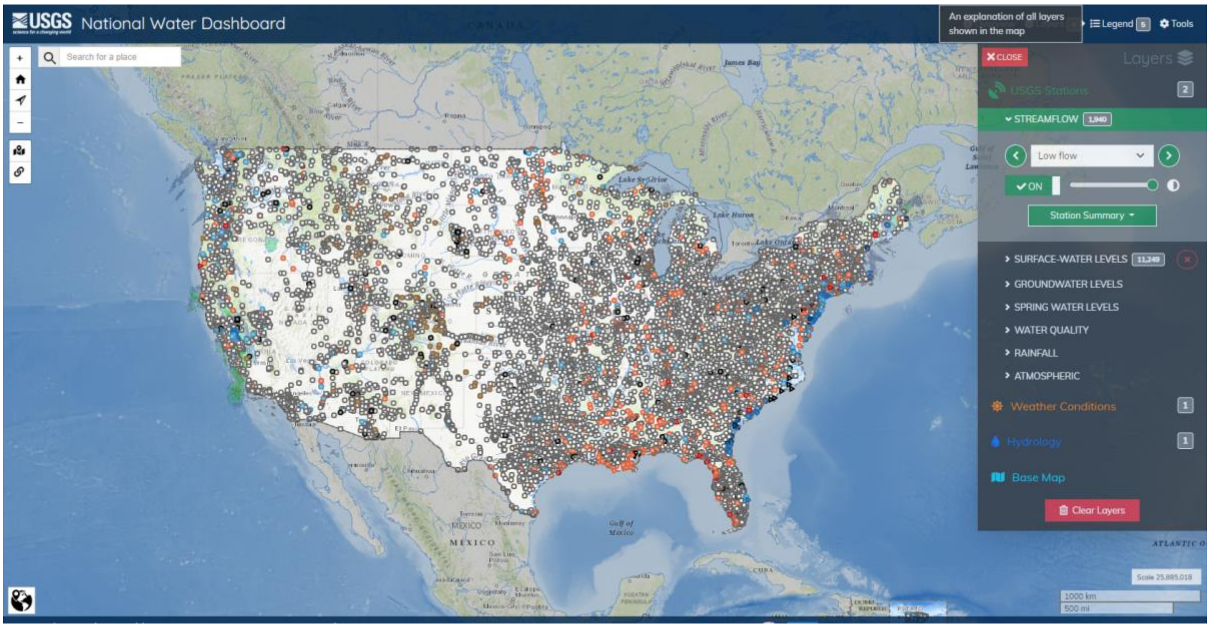


Figure 19. The National Water Dashboard by USGS showing stations with low flow status (Source: USGS, 2022a).

USGS Station Summary

NWS Flood Status		
In major flood stage	0	0.0%
In moderate flood stage	0	0.0%
In minor flood stage	0	0.0%
In action stage	0	0.0%
Not flooding	948	49.9%
Flood stages not established	949	49.9%
No measurement	3	0.2%
Day-of-Year Status		
All-time high for this day-of-year	0	0.0%
Much above normal for this day-of-year	0	0.0%
Above normal for this day-of-year	0	0.0%
Normal for this day-of-year	0	0.0%
Below normal for this day-of-year	995	52.4%
Much below normal for this day-of-year	440	23.2%
All-time low for this day-of-year	187	9.8%
Not ranked - insufficient record	41	2.2%
Not ranked - stream not flowing	237	12.5%
Increasing and Decreasing		
Value increasing	252	13.3%
Value not changing	1,249	65.7%
Value decreasing	398	20.9%
No measurement	1	0.1%
Flagged Values		
No value flag	1,900	100.0%

Figure 20. Station summary showing percentage of stations with low flows in the USGS water dashboard (Source: USGS, 2022a).

In the USGS National Water Dashboard, the streamflow status is classified as below normal and above normal based on the percentile of existing streamflow records on that day-of-the-year. The flow classification is as given in the Table 15. It is to be noted that a gauge is not ranked when there is less than 10 years of record, or a current streamflow value is not available.

Table 15. Streamflow classifications adopted in the National Water Dashboard (Source: USGS, 2022a).

Flow classification	Percentile
All-time low for this day	0th percentile (minimum)
Much below normal	< 10th percentile
Below normal	10th – 24th percentile
Normal	25th – 75th percentile
Above normal	76th – 90th percentile
Much above normal	> 90th percentile
All-time high for this day	100th percentile (maximum)

The 'Legend' tab gives the explanation of all layers on the map. For example, the legend for streamflow indicates the classification of stations with different ranges of flows based on colour coding as shown in the Figure 21.

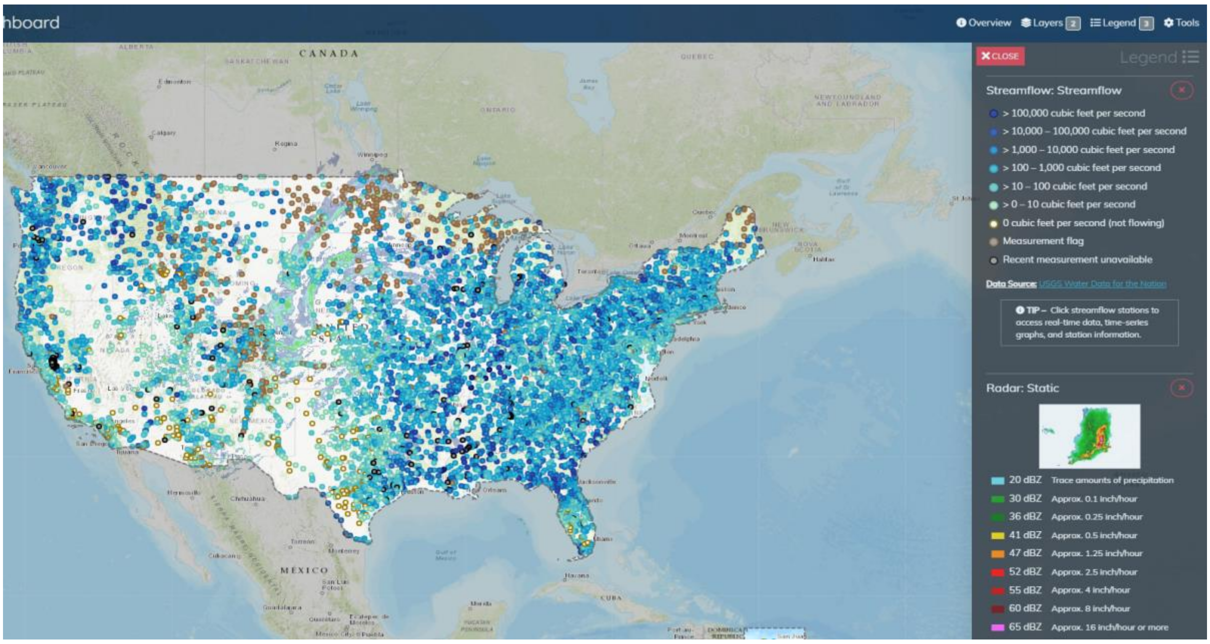


Figure 21. Legend (on the right side) showing different colours for different flow ranges (Source: USGS, 2022a).

For the 'Surface-Water Levels' layer, there are options for selecting flood status of stations, rising and falling status, details of streams, lakes, estuaries, wetlands and tidally influenced stations. Under the 'Water Quality' tab, there is a list of water quality parameters such as dissolved oxygen, water temperature, pH, turbidity, suspended solids and others. For each water quality parameter, station types, measurement parameters, day-of-year status, increasing and decreasing values, flagged values and data age are shown. Additionally, a summary of rainfall and status of various atmospheric parameters can be viewed for all the stations.

In addition to the station summary, near real time discharge, water level and quality details of each station (river, groundwater, lake or wetland) can be obtained by selecting the relevant station on the map. For example, the discharge of Mississippi River at Baton Rouge, LA as shown in Figure 22 where temperature, discharge, water level, specific conductance, DO, pH etc. can also be selected.

Figure 22. The dashboard showing discharge of River Mississippi at Baton Rouge (Source: USGS, 2022a).

Moreover, when the 'Data' tab of the window is selected, all the current and historical data pertaining to hydrology and water quality for that station can be availed. Time series of daily, monthly and annual statistics and peak streamflow for each year are also available. The daily statistics give mean, minimum, maximum and various percentiles of daily flow over the data period.

The National Water Dashboard by USGS is a comprehensive web-based hydrological tool that shows the near real-time hydrological conditions at various hydrological stations all over the U.S. Also, the dashboard enables relative comparison of current conditions at a station with historical conditions. However, the dashboard does not illustrate the quantity of temporal variation of discharge or level of a particular station. Adding such features to the existing framework will enhance the tool's functionality and can be adopted for the Mekong flow monitoring framework.

4.2.4 The Texas Environmental Flow Information Toolkit and Hydrology Dashboard

The Texas Parks and Wildlife Department (TPWD, 2022) has developed the Great Plains Environmental Flow Information Toolkit (GP EFIT), which contains a series of interactive dashboards, analysis tools, data, and publications to monitor streamflow health. This is expected to help the formation of environmental flow restoration strategies with the help of an interactive geospatial framework for the Texas Great Plains. A screenshot of the hydrology dashboard is shown in Figure 23.

The Selection Index on the left side of the dashboard allows the users to select flow regime component, river basin, USGS streamflow gauge and water use type. The flow regime component has different options such as seasonal or annual subsistence or baseflow component and can be selected with a dropdown menu. The river basin menu allows user to select a river basin of interest within the Great Plains Region of Texas. When a USGS gauge is selected, a pop-up window is opened with information on data sources and analytics. The target flows, hydrologic alteration percentages and flow deficits are shown in the next column, as in Figure 24. The water user type can also be selected from the list.

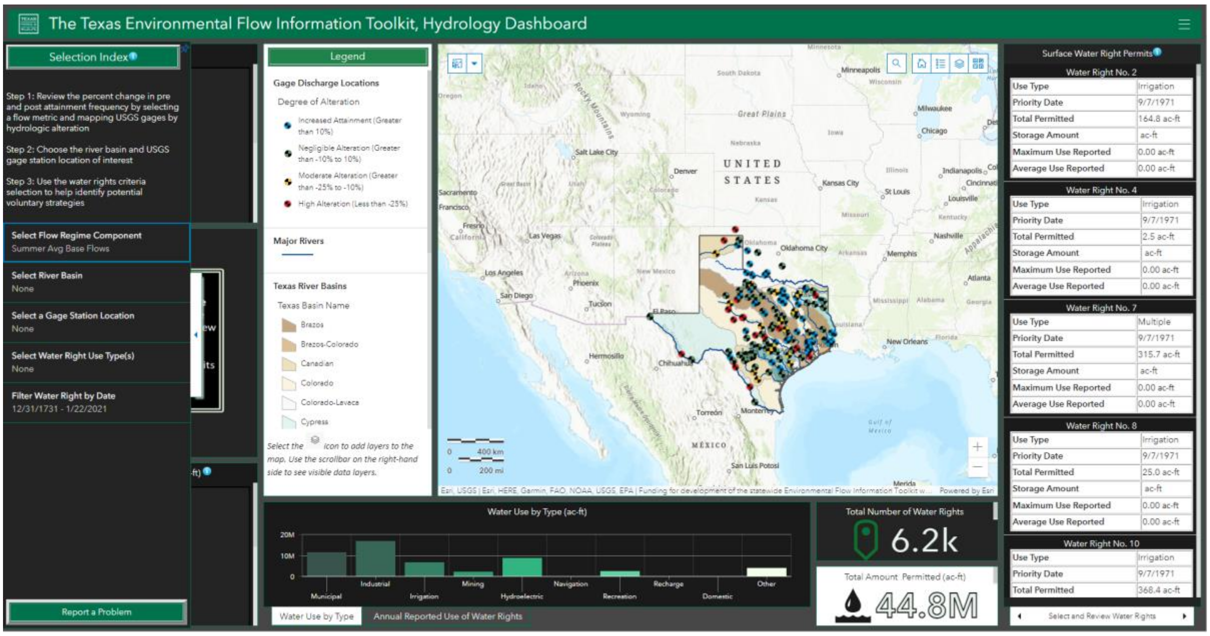


Figure 23. Screenshot of the hydrology dashboard by Texas Parks and Wildlife Department (Source: TPWD, 2022).

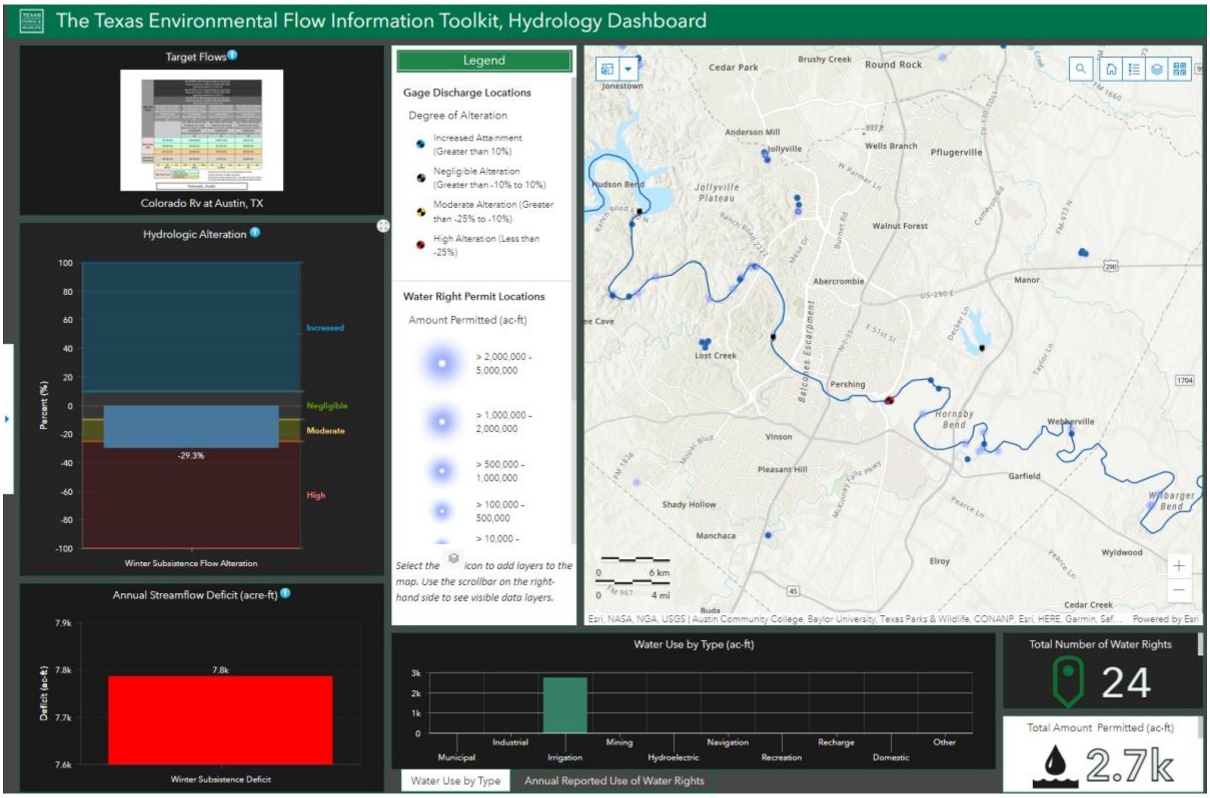


Figure 24. Screenshot of the GP EFIT dashboard showing target flows, hydrologic alteration and annual streamflow deficit on the left side (Source: TPWD, 2022).

The target flow tab shows a table of environmental flow targets for the selected station that includes all the flow types (subsistence, base flows, high flow pulse) for each of the seasons. For example, a screenshot of the target flow table for the Colorado River at Austin is shown in Figure 25. The target flow table gives the expected flows during different seasons for subsistence, base and high flows based on historical records.

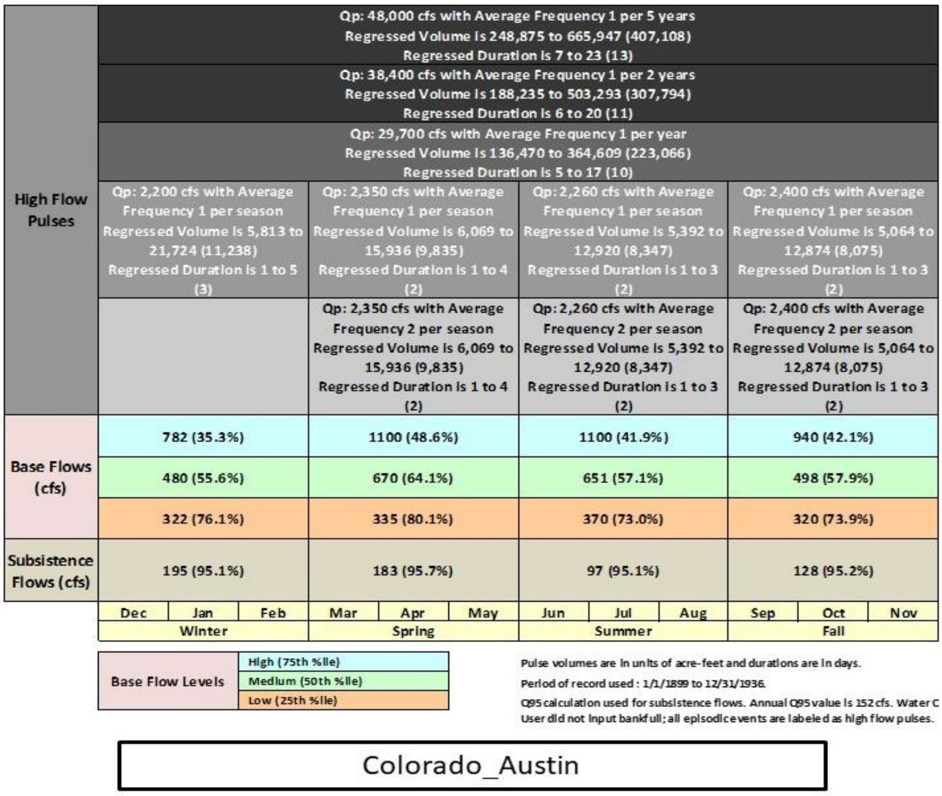


Figure 25. Image showing the target flows for the Colorado River at Austin (Source: TPWD, 2022).

The dashboard determines hydrology-based flow targets using Indicators of Hydrologic Alteration (IHA) and Hydrology-Based Environmental Flow Regime (HEFR). The default criteria used to classify environmental flows are:

- High flow pulses - all flows that exceed 75% of flows for the period
- Small flood event – a high flow pulse with a recurrence time of at least 2 years
- Large flood event – a high flood pulse with a recurrence time of at least 10 years
- Extreme low event – a flow in the lowest 10% of all low flows in the period

The outputs from the IHA were then used as inputs for the HEFR to calculate the chart as shown in Figure 25.

The degree of flow alteration is quantified using the most recent 10 years of the USGS flow data and compared with the attainment frequencies of the pre-alteration period. The resulting changes are reported as a relative reduction compared to the baseline rather than as a simple change in the frequency of attaining the flow targets. Adopting this methodology, the categories of degree of alteration are:

- Increased attainment: greater than 10%
- Negligible alteration: -10% to 10%
- Moderate alteration: -10% to 25%
- High alteration: less than -25%

For example, in Figure 25 above the Hydrologic Alteration for the Colorado River at Austin is -29.3%, which is a high degree of alteration. The annual streamflow deficit is the difference between target flow volume and the volume of water available in the current season. As in Figure 25, the winter subsistence flow deficit of the Colorado River at Austin is 7,800 ac-ft (acre-feet).

4.2.5 North America WaterWatch

The North America WaterWatch (NAWW) web page hosted jointly by the U.S. and Canada as a part of International Joint Commission (IJC) shows a map of real-time streamflow compared to historical streamflow for the day of year for all the major hydrologic stations across the U.S. and Canada. When selecting a particular station from the map, a summary of near-real time water resources conditions is shown along with hydrograph, peak flows and forecast. The screenshot of the web page is shown in Figure 26.

The 'Peak' tab shows the current water level or discharge, recent maximum in the previous 365 days and the highest recorded peak discharges or water levels for the selected station.

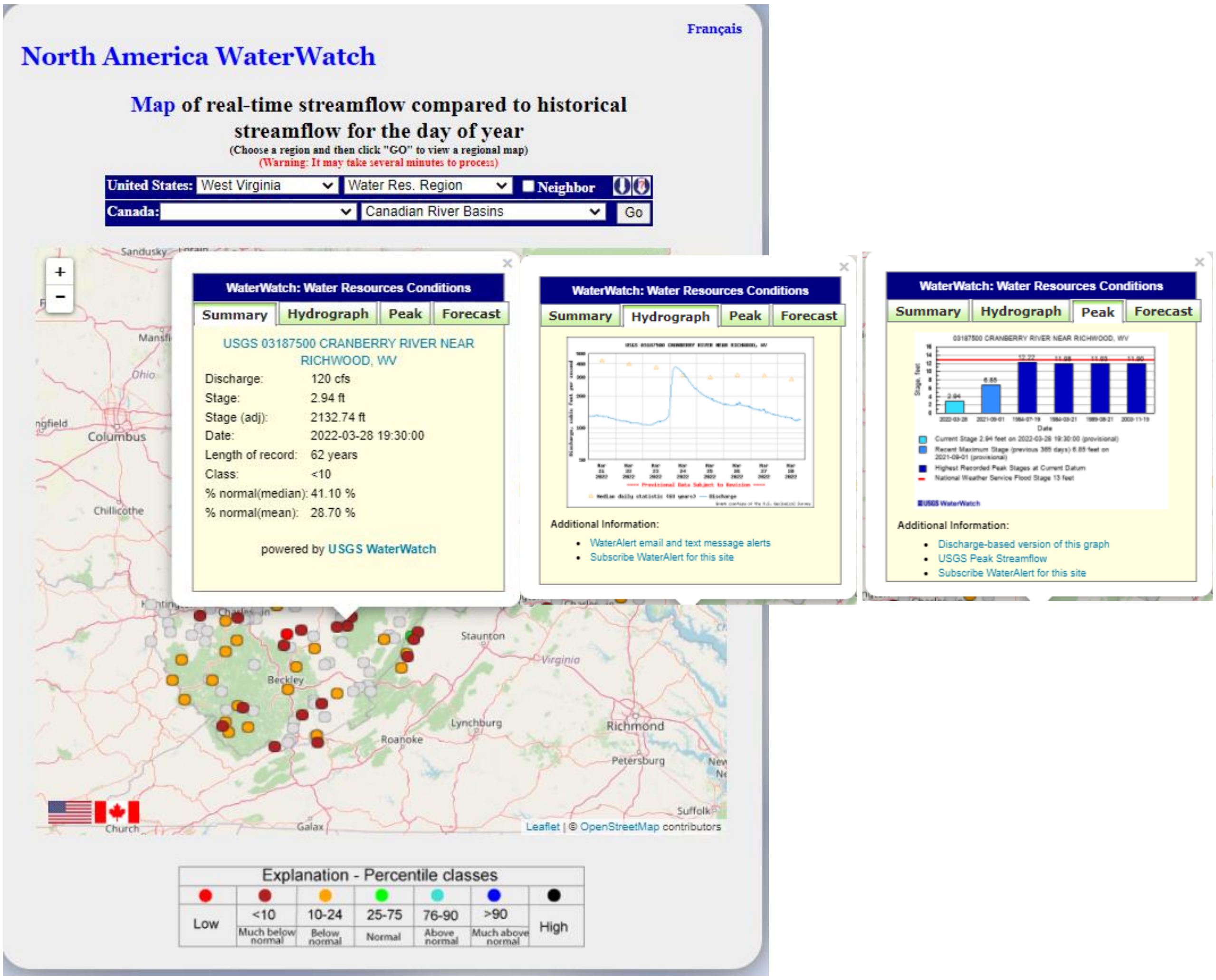


Figure 26. North America WaterWatch map showing real-time streamflow compared to historical streamflow for the day of year (Source: International Joint Commission, 2022).

The WaterWatch interactive web tool by USGS (2022b) can be used for accessing current streamflow, flood, drought, past flow/runoff and annual summaries for different hydrological stations in the U.S. The advantage of this tool is that the real-time streamflow, drought, flood and past flow/runoff maps are displayed in the same page as in Figure 27 and users can select whichever map they like to see the details. For example, when a particular station (coloured circles) from the 'Current Streamflow' map is selected, the water resources conditions of that station is displayed in a smaller window as in the North America WaterWatch dashboard.

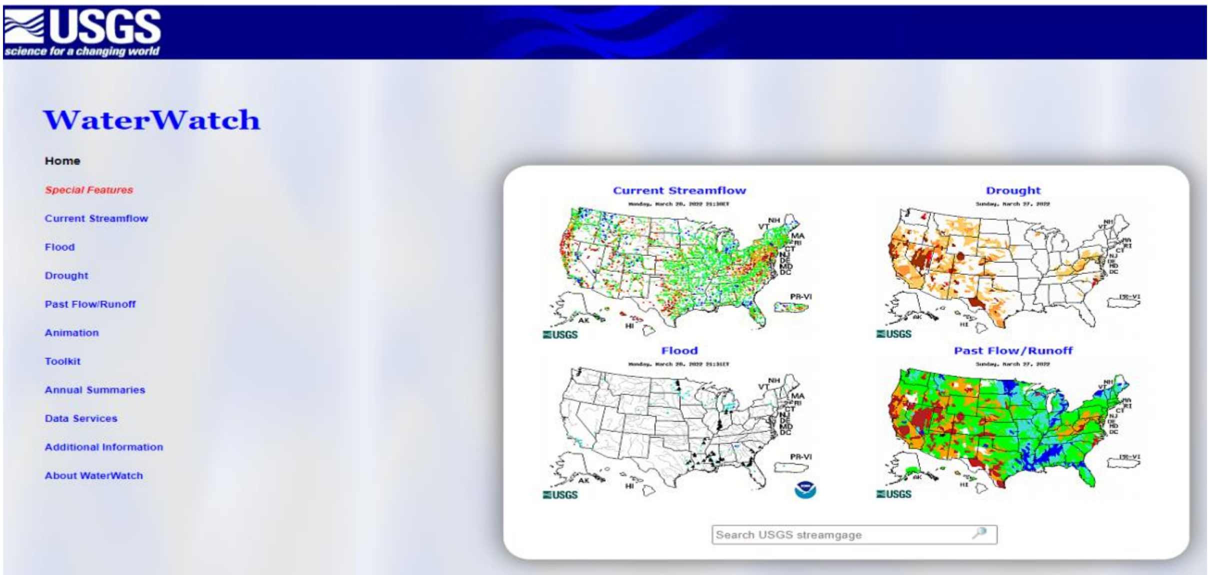


Figure 27. Web page of the USGS WaterWatch showing various in the same page (Source: USGS, 2022b).

Maps showing real time, 7-day, 14-day, 28-day and monthly average streamflow compared to historical streamflow can be viewed if the 'Current Streamflow' tab on the left side of the maps is selected. The 'Flood' tab shows features including dynamic map of flood and high flow conditions, table showing locations above flood stage, number of USGS gauges in near flood or flood, flood tracking chart and a cumulative streamflow hydrograph builder as illustrated in Figure 28.

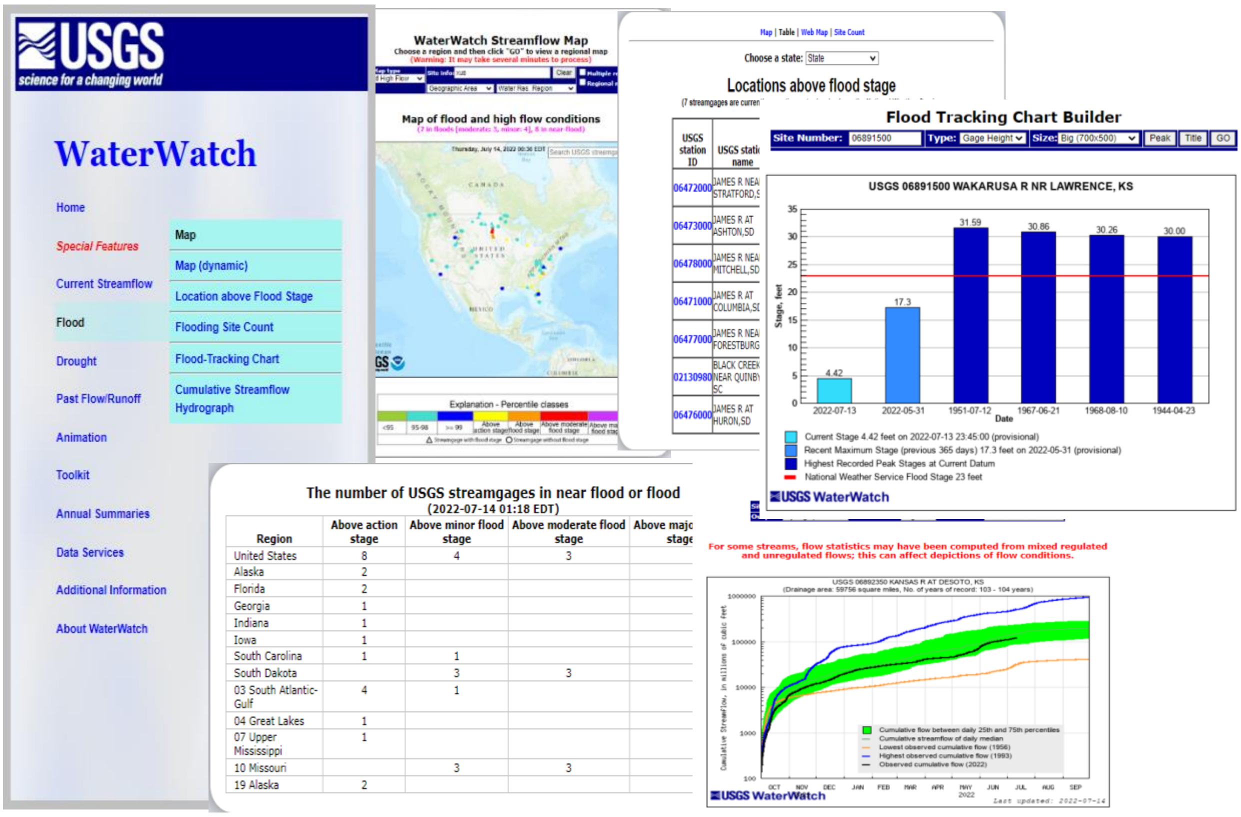


Figure 28. Windows depicting various components of the 'Flood' tab of USGS WaterWatch dashboard (Source: USGS, 2022b).

Similar details are also available for ‘Drought’ tab. Maps comparing below normal 7-day, 14-day, 28-day and monthly average streamflow with historical streamflow can be viewed by selecting the ‘Drought’ tab. Site and state duration hydrographs, cumulative streamflow hydrograph, drought table, map comparison, and record low flow map are also useful features of the ‘Drought’ tab. The map comparison is a very useful feature which compares the streamflow maps of any two periods (daily, monthly etc.) for a particular geographical area or water resources region in the U.S. The comparison of streamflow maps is shown in Figure 29.

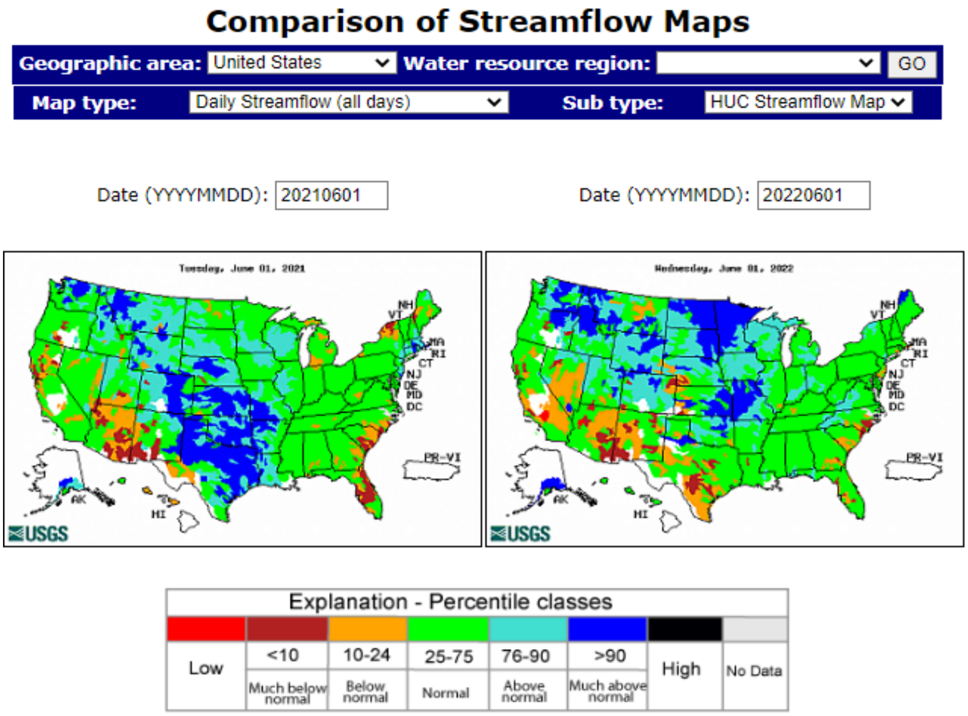


Figure 29. Streamflow maps comparison feature in the WaterWatch dashboard (Source: USGS, 2022b).

Another feature of this web tool by USGS is the ‘Animation’ tab, by which one can create animated streamflow map for a particular period. This is useful for viewing the changes of streamflow and flood over the selected period on a daily or monthly time step. The ‘Annual Summaries’ tab produces overview of the streamflow for the selected summary year (from 2005 onward) along with regional patterns, seasonal characteristics, and high and low flows in a report format. This is a very handy tool to see an overall picture of streamflow as in national overview, regional patterns, seasonal characteristics for each state in the U.S. and the high and low flows.

The ‘Special Features’ tab has Flow Duration Curve builder, by which flow duration curves for any site can be built using a begin date and end date. Another feature is the ability to create duration hydrograph with backdrop of monthly flow percentiles, which presents a history of streamflow as in Figure 30. This feature is almost similar to the Articles 6A and 6C flow monitoring frameworks by MRC with some changes in the method of estimating thresholds. While 6A and 6C define thresholds based on the Annual Recurrence Intervals (ARI), the streamflow duration hydrograph as in Figure 30 classifies the flows based on percentile classes.

The ’Special Features’ tab also has options for viewing popular streamflow analysis tools for a particular stream gauge and state.

The ‘Data Services’ tab provides option for downloading various data sets which are used in the visualisation tools. Geographic Information System (GIS) shapefiles of streamflow conditions can also be downloaded.

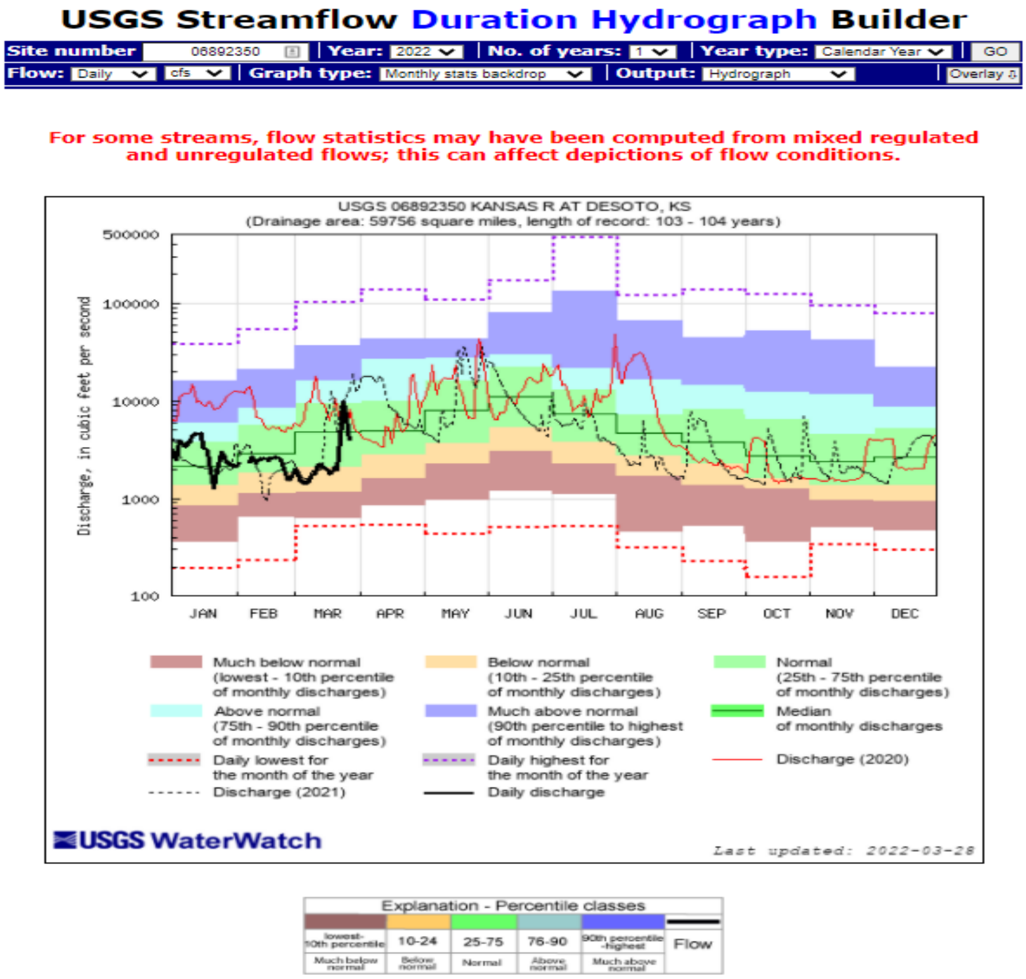


Figure 30. Streamflow duration hydrograph builder by USGS showing discharges for 2020, 2021 and 2022 with background information (Source: USGS, 2022b).

The WaterWatch by USGS is a comprehensive flow monitoring and visualisation tool with many features incorporated in it as described above. The advantage of WaterWatch is that hydrological conditions of all the major gauges in the U.S. can be navigated from a single web page and hence is easy to use. Moreover, real-time and historical streamflow, their comparisons and flood and drought conditions can be visualised differently. A similar approach can be adopted to develop a unified river flow monitoring web-based tool for MRC, incorporating additional flow indicators identified in the review.

4.2.6 Water Office Canada

The hydrometric data web tool by Water Office Canada shows real-time water level and discharge for Canadian streamflow stations on a map view. When a station is selected from the map view, its hydrometric data can be viewed in graph or table format. The data contains mainly discharge and water level information. The Figure 31 below shows real-time discharge, mean, minimum, maximum, upper and lower quartile ranges of discharge for a particular station.

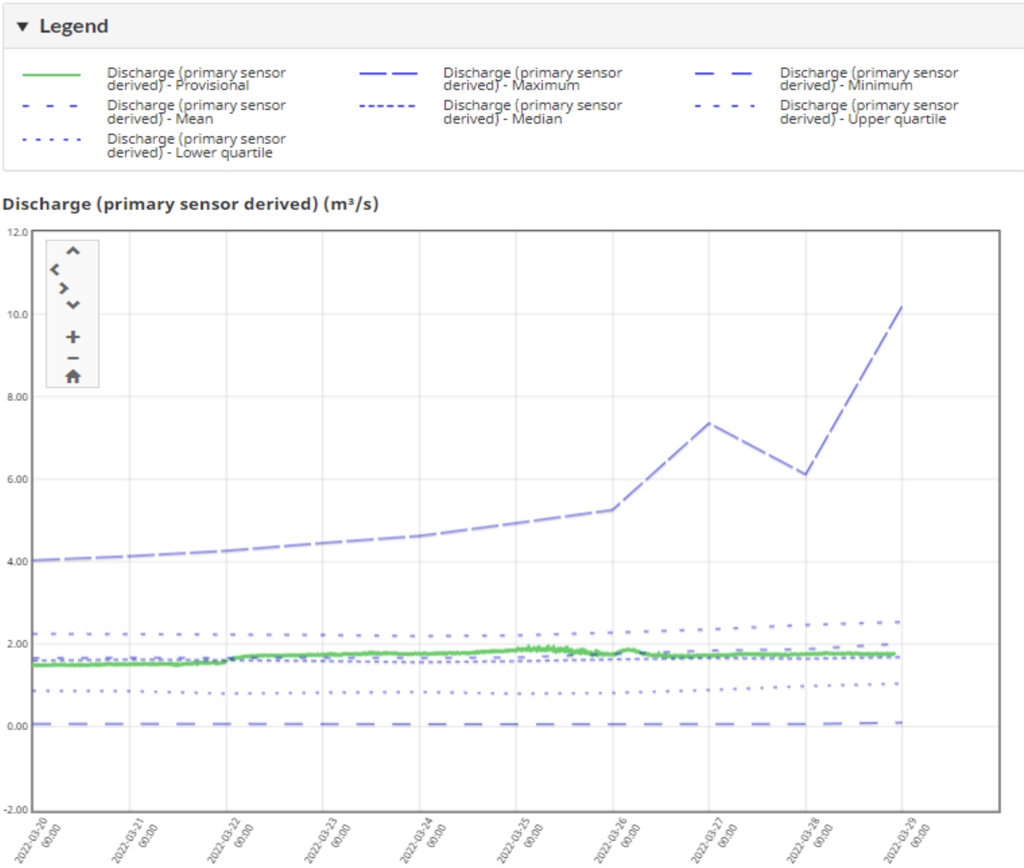


Figure 31. Real-time hydrometric data graph for a river station in Canada (Source: Water Office Canada, 2022).

Station information and data collection history are also available on the same page of the web-based data tool.

The webpage by the Water Office Canada is a simple visualisation web tool. The MRC uses a similar tool to depict near real-time discharge and water levels in the Mekong.

4.2.7 UK Water Resources Portal

The UK Water Resources Portal is an interactive web-based tool developed by the UK Centre for Ecology and Hydrology to monitor the hydrological conditions on a near real-time basis. Data are available in raw form as well as standard indices. The portal shows daily river flow data in near-real time for various river flow stations.

The basemap of the UK showing the river flow conditions across various river flow stations is illustrated in the Figure 32 below. The colour differences of river stations indicate the deviations of the flows (whether above or below normal flows) from the normal flows. The right-hand side of the figure illustrates the raw data regarding the present river flow as compared to normal, above and below normal flows. The data type can be changed from raw data to standardised indices and time scale from daily to monthly. Various graph types such as 'Regime bandings' (as shown in Figure 32), 'Time-series', 'Time-series with envelopes' (showing current, mean, minimum and maximum flows), 'Historical comparison: five droughts' (comparison of current flow with last five major droughts), and 'Historical comparison: select up to three years' (comparison with any three years) can be selected from the drop down list.

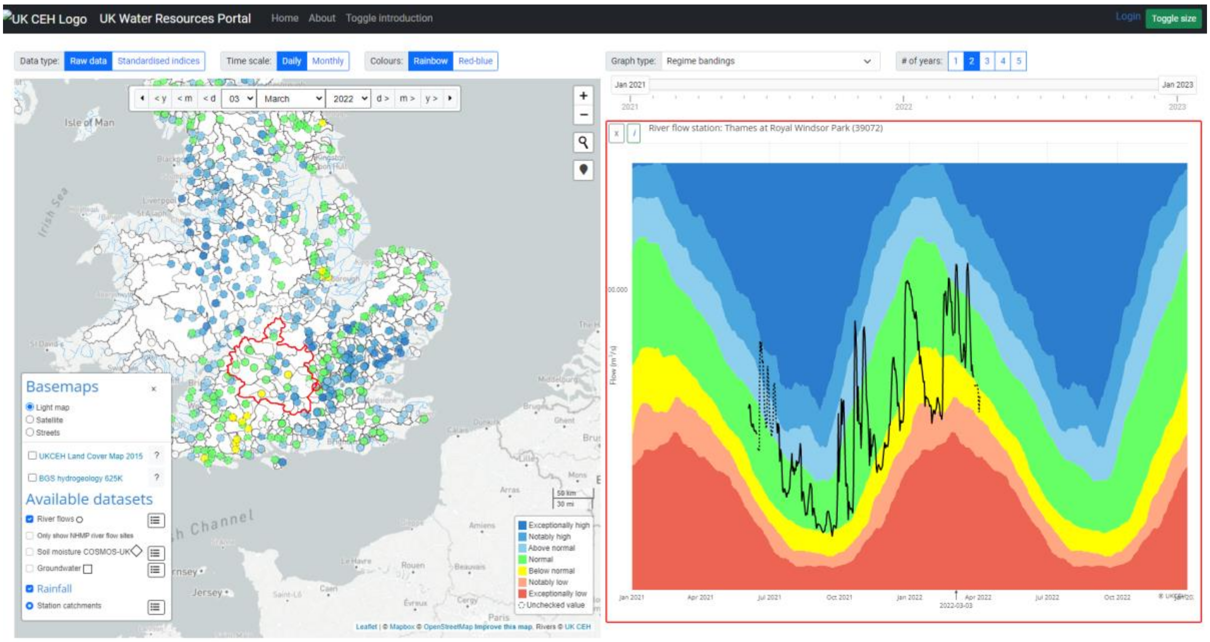


Figure 32. The UK basemap showing river flow conditions at various stations (left panel) and the regime bandings (right panel) (Source: UKCEH, 2022).

Additional map layers such as rainfall, groundwater levels, and soil moisture are also displayed as raw data and standardised indices. For example, the index Standard Streamflow Index (SSI) demonstrates the deviation of streamflow from the long-term average for a given month and location. The index can be compared between different temporal and spatial scales. The SSI is calculated using average monthly river flows for each catchment using the Tweedie distribution and standard period of 1961 – 2010. The screenshots of graphs showing the SSI of river flows are shown in the Figure 33 below. The left panel shows the time series SSI, and the right panel shows the historical comparison with five droughts.

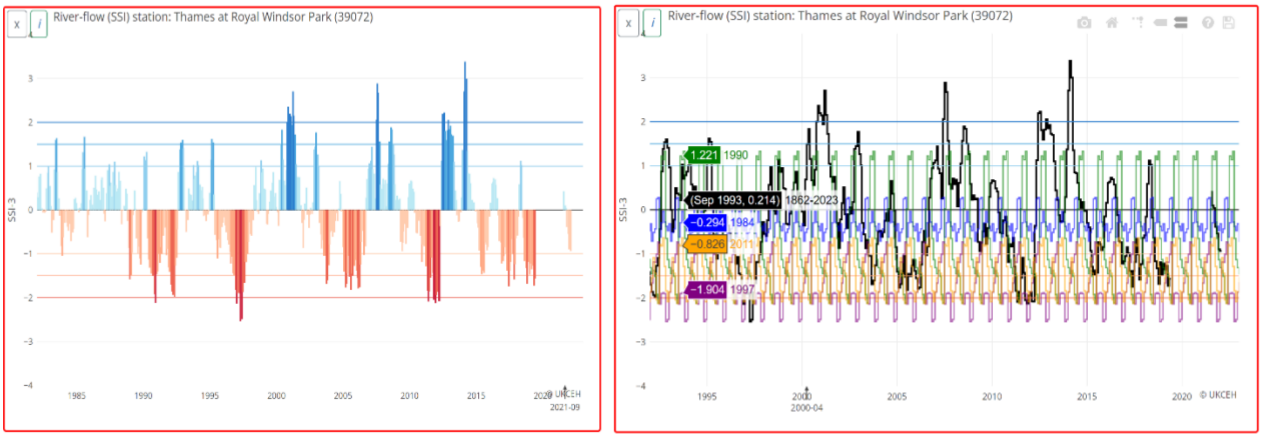


Figure 33. Images from the UK Water Resources Portal showing the SSI of a river station with a) time series SSI and b) comparison with five droughts (Source: UKCEH, 2022)

The negative values of SSI indicate that the flows or levels are lower than average, whilst postive values indicate that the flows or levels are above average. The values greater than two indicate very high flows and values less than two indicate very low flows.

Thus the UKWRP shows different types of time series plots, including simple time series plot, a time series plot with recorded daily maximum and minimum and the long-term average, regime bandings, comparisons to five pre-selected major drought events and the option to select three years of data of users choice. The UKWRP functionalities are brought together using a combination of technologies (Barker et al., 2022) and the summary of those processes and technologies are shown in Figure 34.

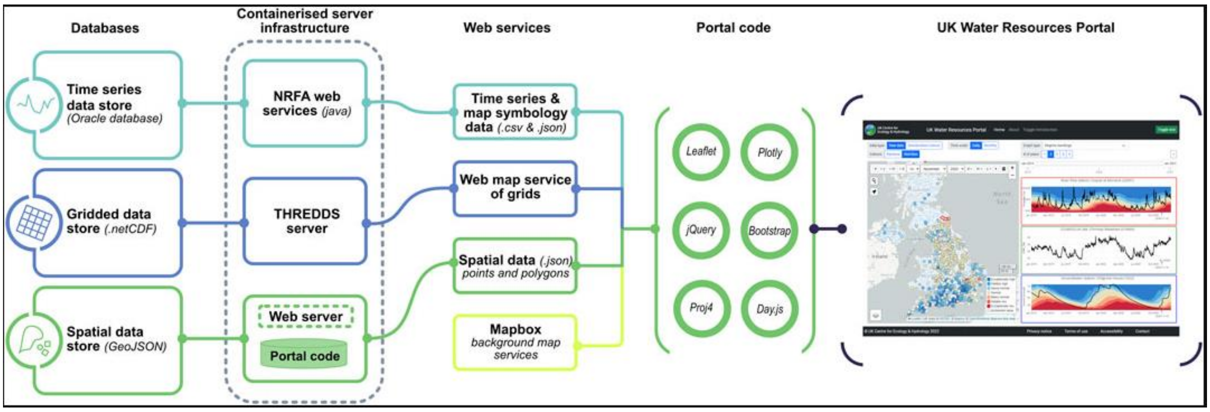


Figure 34. Architecture of the UKWRP showing the processes and libraries used (Source: Barker et al., 2022).

The UK Water Resources Portal is a handy web-based tool that visualises hydrological data simply. Some of the features such as representation of standardised indices and showing map and graphs on the same page and side by side can be adopted for the Mekong flow monitoring dashboard. Moreover, the option is to see the current flows in comparison with past events such as record droughts and low flows.

4.2.8 Mekong Dam Monitor by Stimson Centre

The Mekong Dam Monitor is a web-based tool Stimson Center and Eyes on Earth Inc. developed to report near real-time river conditions and data downloads across various indicators in the Mekong Basin. This is enabled by using remote sensing, satellite imagery and GIS analysis.

The home page illustrates the 'Spotlight' section, which sheds light on critical information and alerts regarding the upstream dam releases over the week. The page also demonstrates the dam releases downstream, river levels and weather information. Another important feature is the demonstration of river levels at selected stations. The feature, as shown in the screenshot below (Figure 35), shows the actual water level and the expected water level at that time. This is a very useful tool for the stakeholders and the public alike. The previous week weather condition section contains information on surface wetness anomaly, precipitation anomaly, surface temperature anomaly and snow cover. The change in reservoir storage volumes over the last seven days is also depicted as a map view in the page, depicting the impact on dams. A dam is considered most impacted when there is a change of more than 50 million cubic meters of water over the previous seven days. The storage volumes of five large dams and other dams at different time steps of recent year are depicted under the Section 'Reservoir Volume' as shown in Figure 36. The current and potential storage volumes of 45 dams across the Mekong and its tributaries are also demonstrated in the Mekong Dam Monitor.

Figure 35. Screenshot of the Mekong Dam Monitor showing the actual and expected water levels at four different river stations (Stimson Center, 2022).

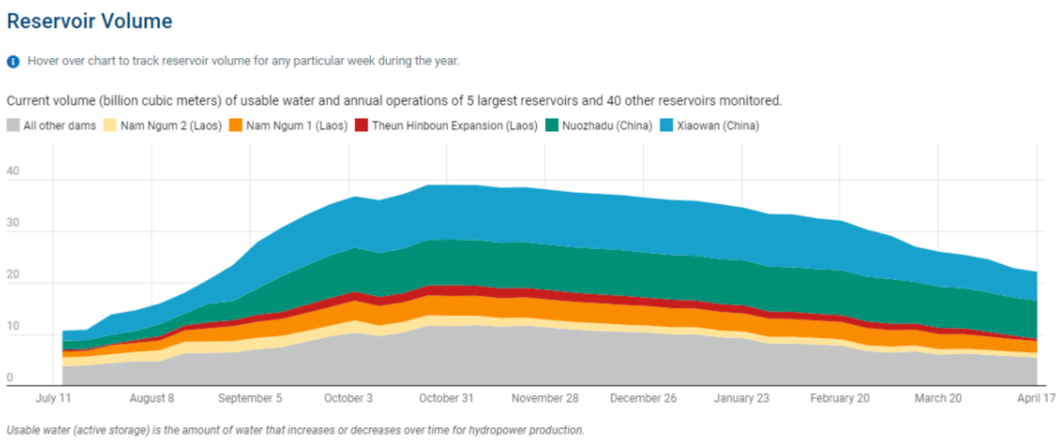


Figure 36. Screenshot of the Mekong Dam Monitor showing the active storage and annual operations of five largest and 40 other reservoirs (Source: Stimson Center, 2022).

The ‘Virtual Gauges’ tab of the Mekong Dam Monitor shows the summary of virtual gauges along the Mekong and details about dam profile, operation curve and satellite imagery of various dams and reservoirs. The operating curves show the storage volume of the dam for the current as well as previous few years on a daily basis.

The ‘Cascade Analysis’ tab illustrates the Lancang cascade operations in China as shown in Figure 37. The page shows the status of water levels and flows of different dams, their relative changes compared to the previous period, electricity production status etc.

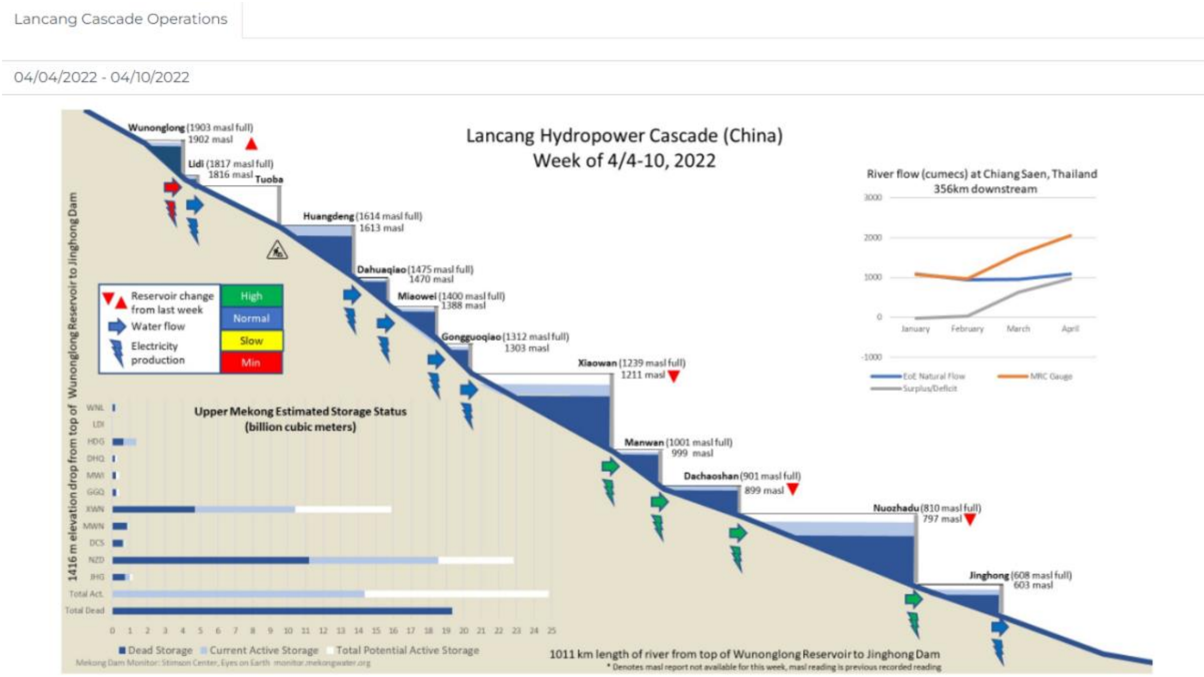


Figure 37. The status of cascade dam operations and changes on a particular week. (Source: Stimson Center, 2022).

The Mekong Dam Monitor is a comprehensive tool for monitoring water flows at different dam locations. It informs the stakeholders about the near real-time dam operations and their impacts on the flows at selected stations. However, it lacks information about the trends of river flows and levels at all the major downstream stations, especially in the Lower Mekong Basin (LMB).

4.2.9 U.S. Drought Monitor

An example of a drought monitoring tool is the U.S. Drought Monitor map. The U.S. Drought Monitor map classifies the areas under drought by using various drought indicators. The intensity of drought is indicated by the colour grade used in the map as shown in Figure 38.

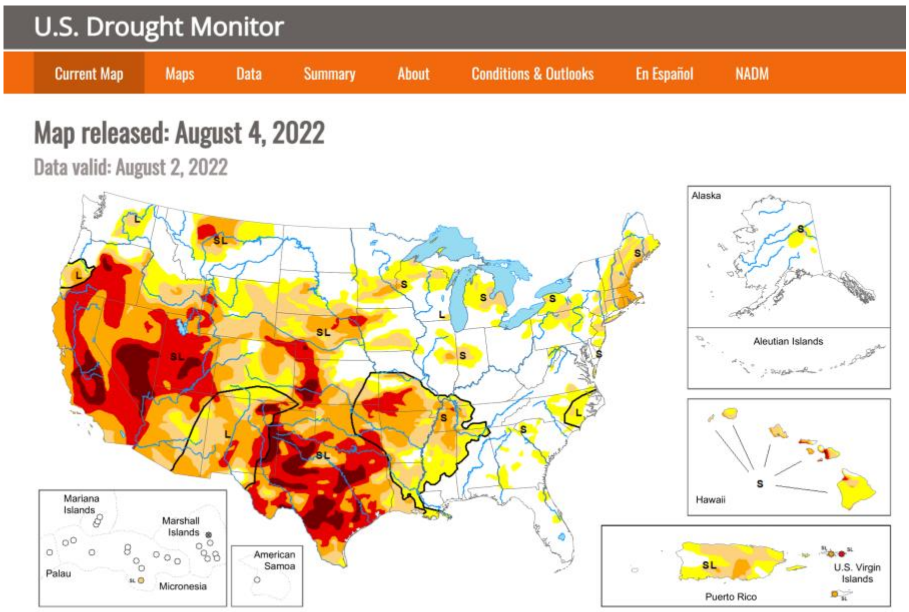


Figure 38. Screenshot of the U.S. Drought Monitor map (Source: National Drought Mitigation Center, 2022)

The drought intensity for each area is categorised based on five key indicators along with other objective indicators (National Drought Mitigation Center, 2022). The categories and indicators used to classify the drought intensity are given in Table 16.

Table 16. Category of drought intensity and indicator ranges (Source: National Drought Mitigation Center, 2022)

Category	Description	Ranges				
		Palmer Drought Severity Index (PDSI)	CPC Soil Moisture Model (Percentiles)	USGS Weekly Streamflow (Percentiles)	Standardised Precipitation Index (SPI)	Objective Drought Indicator Blends (Percentiles)
D0	Abnormally Dry	-1.0 to -1.9	21 to 30	21 to 30	-0.5 to -0.7	21 to 30
D1	Moderate Drought	-2.0 to -2.9	11 to 20	11 to 20	-0.8 to -1.2	11 to 20
D2	Severe Drought	-3.0 to -3.9	6 to 10	6 to 10	-1.3 to -1.5	6 to 10
D3	Extreme Drought	-4.0 to -4.9	3 to 5	3 to 5	-1.6 to -1.9	3 to 5
D4	Exceptional Drought	-5.0 or less	0 to 2	0 to 2	-2.0 or less	0 to 2

4.3 Examples from Australian water utilities and other agencies

The Australian water utilities and water management agencies have near real-time storage and flow information dashboards for different states and departments. Some of the examples are illustrated below.

4.3.1 Melbourne Water

Melbourne Water is a government-owned authority responsible for much of the water system in Melbourne, Victoria, Australia. It manages and protects Melbourne's major water resources and supplies high quality water to water retailers.

The Melbourne water dashboard shows the daily river level, flows and water storage in near real-time for different monitoring sites across Melbourne. Historical monthly water storage levels can also be displayed for comparison purposes. The rainfall (blue circles) and river levels (yellow circles) dashboard show different monitoring sites on an interactive map. When selecting a particular location, rainfall or river level or flow can be viewed hourly, daily, weekly and monthly. The selection period can range from one day to three years or a custom range. The chart in Figure 39 below shows the river level for a monitoring site for the last 30 days in the form of mean, minimum and maximum values.

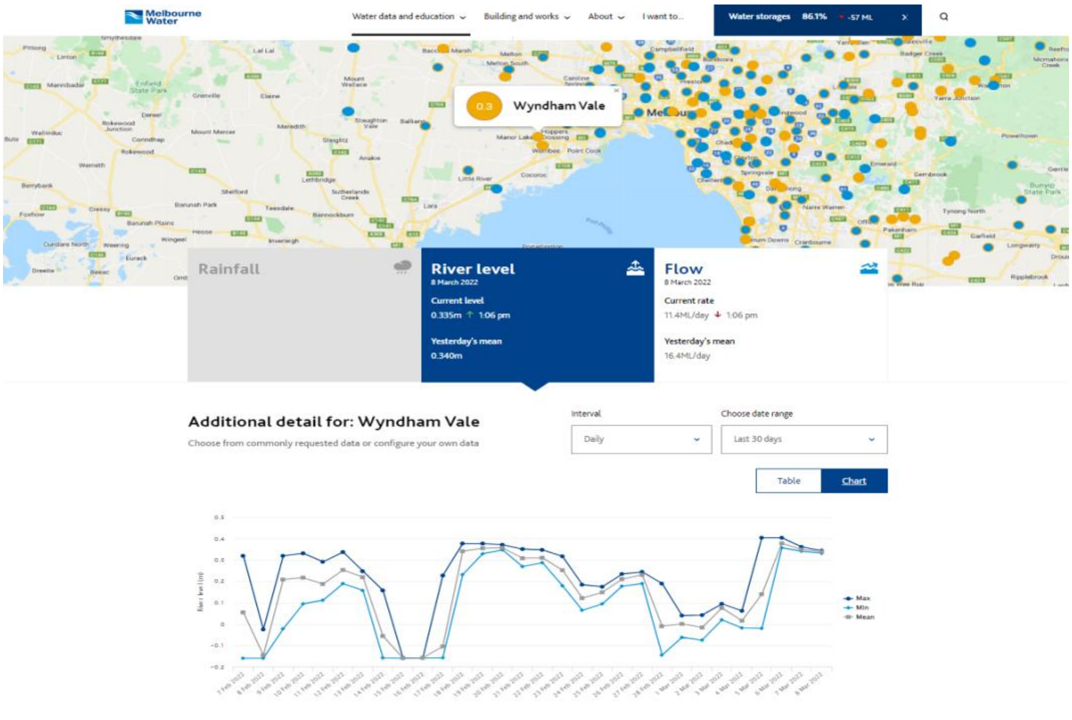


Figure 39. Melbourne Water dashboard showing river levels for a monitoring site in Melbourne, Australia (Source: Melbourne Water, 2022).

4.3.2 WaterNSW

WaterNSW is a state-owned authority operating rivers and water supply systems in New South Wales (NSW), Australia. To monitor the surface and groundwater resources in NSW, WaterNSW operates a range of water monitoring programs. This involves a collection of field data using digital sensors and logging devices and collating them to a central database system. The collated data is visualised using a digital tool named WaterInsights, which show a wide range of water related data and forecasts.

The WaterInsights feature as in Figure 40 shows the near real time river flow rate and river levels for the past seven days and seven day forecast for different gauges/stations.

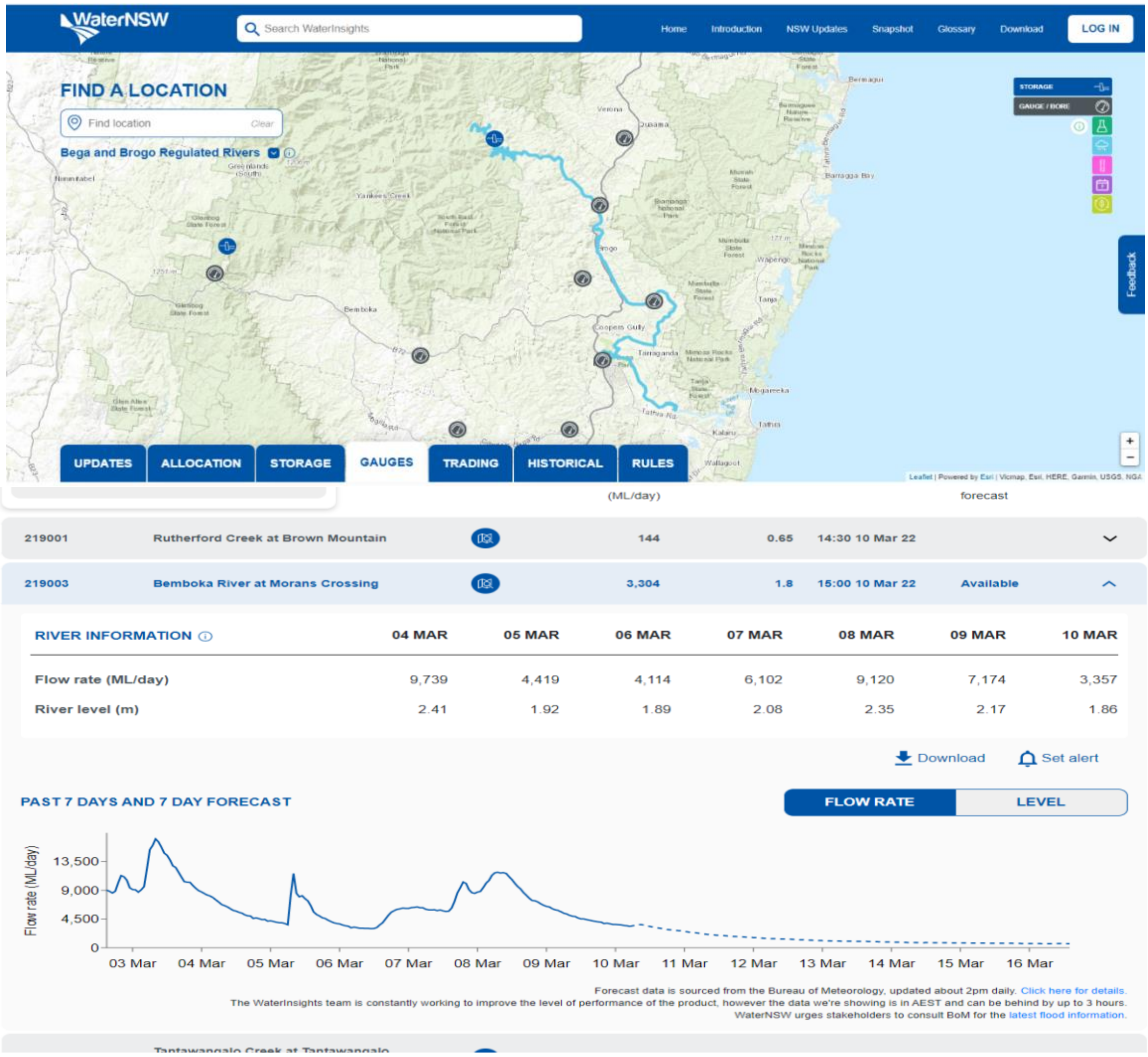


Figure 40. WaterInsights dashboard of WaterNSW showing map view, flow rate, river level and forecast (Source: WaterNSW, 2022).

The WaterInsights tool also depicts storage graphs illustrating historical storage volume, inflow and releases when the ‘Storage’ tab is selected. The flow rate forecast for the next seven days is a useful feature that MRC can adapt for the Mekong. The forecast data is sourced from the Australian Bureau of Meteorology, which uses computer models for streamflow and flood forecasting.

4.3.3 Bureau of Meteorology

The Australian Bureau of Meteorology (BoM) has a monitoring dashboard that shows a snapshot of annual streamflow differences from the average for different hydrological reference stations (Figure 41). It also gives a quick facts sheet about catchment area, stream length, time series start and end date, daily and annual averages etc.

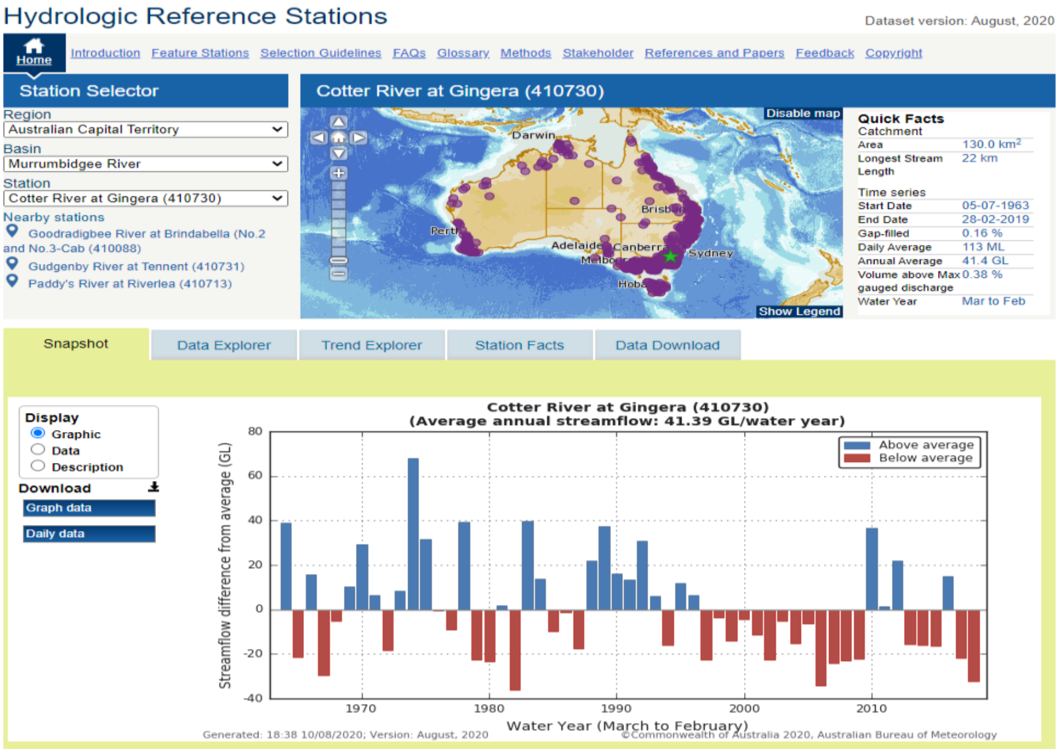


Figure 41. BoM dashboard showing map view of hydrologic reference stations and average annual streamflow (Source: BoM, 2022).

The BoM also has monthly water update pages for rainfall, streamflow, streamflow salinity and water storage. The streamflow map view can be used to view the total monthly flow at each river station and its relationship to past years in terms of decile ranking as classification. As can be seen from the Figure 42 below, there are seven decile groups, which indicate whether the flow is average, below or above average etc. There are options for changing the page's basins, month and year.

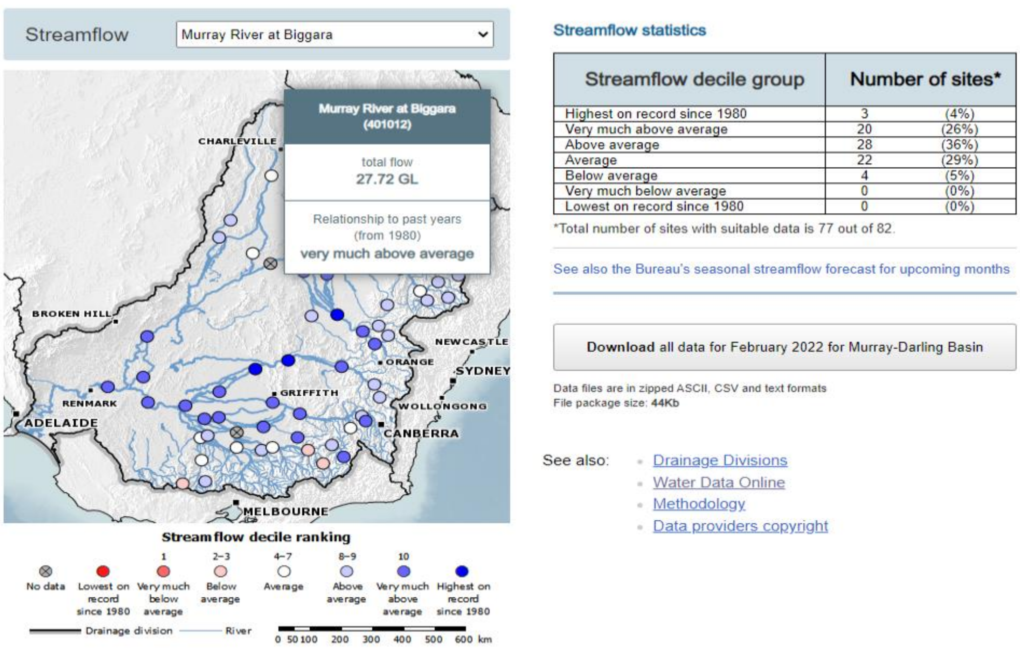


Figure 42. BoM web page showing monthly water updates for a station (Source: BoM, 2022).

4.3.4 Queensland Government Water Monitoring Information Portal

Similar to WaterNSW, the Queensland Government has a water monitoring information portal for different basins and river stations, as shown in Figure 43. The portal offers instantaneous and historic water level, discharge, electrical conductivity, water temperature and rainfall with the latest plots of these variables. The 'Details' tab shows the location details of the station. The flow volume summary in the 'Details' tab shows the daily and monthly minimum, maximum, mean and median volumes.

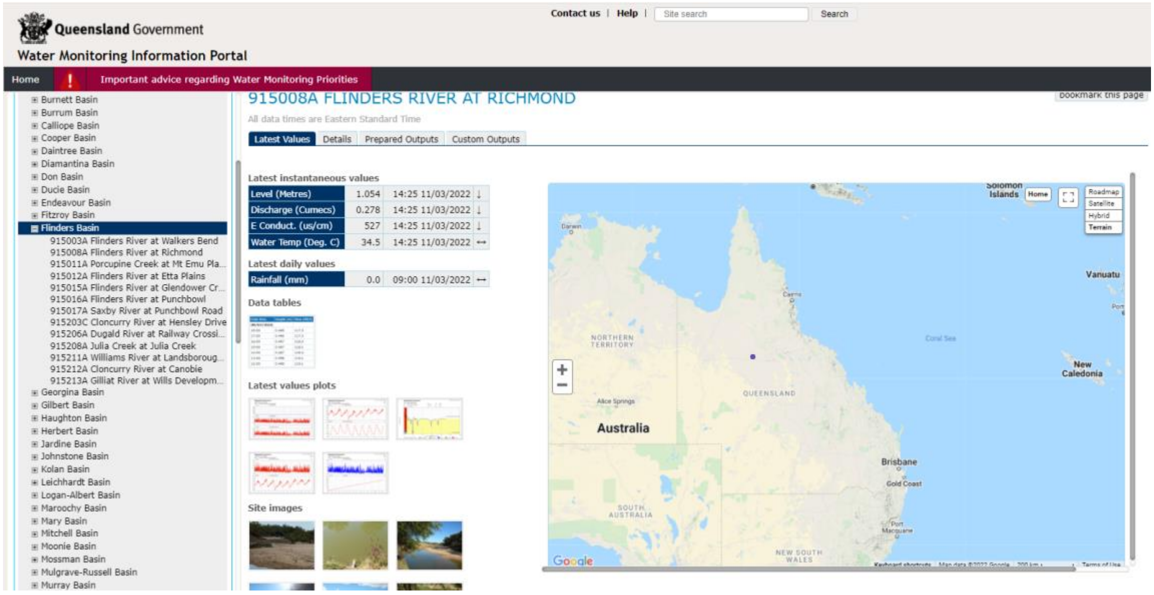


Figure 43. Water monitoring information portal of Queensland Government (Source: Queensland Government, 2022).

The water information portal by the Queensland Government has some features similar to that of current MRC flow monitoring page. For example, the portal shows cross section status of a river station with highest and lowest recorded water levels as in Figure 44, which is similar to that of MRC feature (Figure 7).

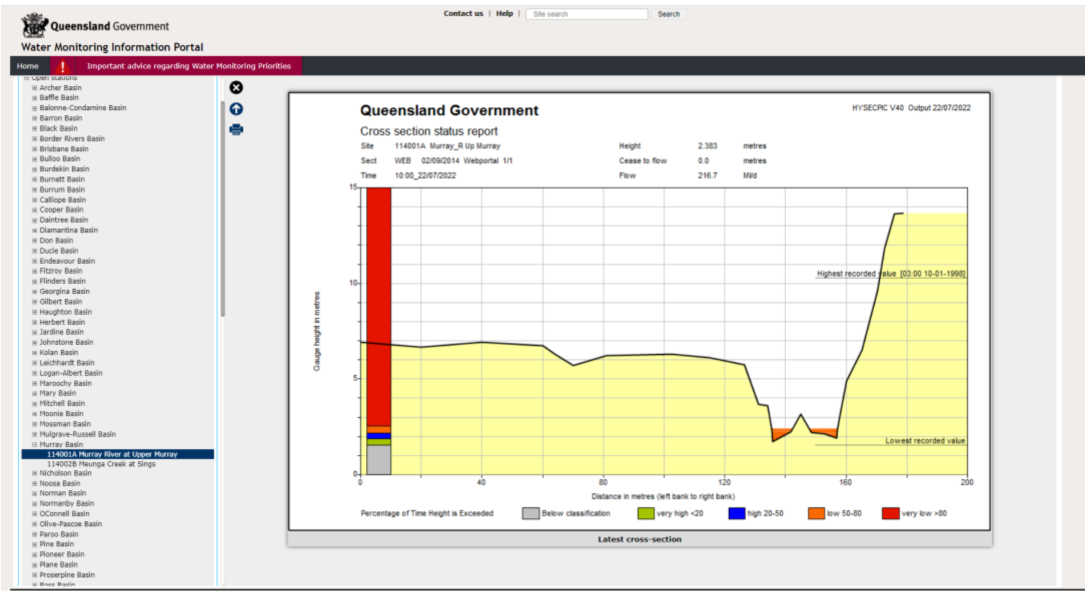


Figure 44. Water monitoring information portal of Queensland Government showing cross-section status report (Queensland Government, 2022).

4.3.5 Water Data South Australia

The Water Data SA portal of the Government of South Australia shows map view of major river stations across South Australia and their details. The screenshot of the portal is shown in Figure 45.

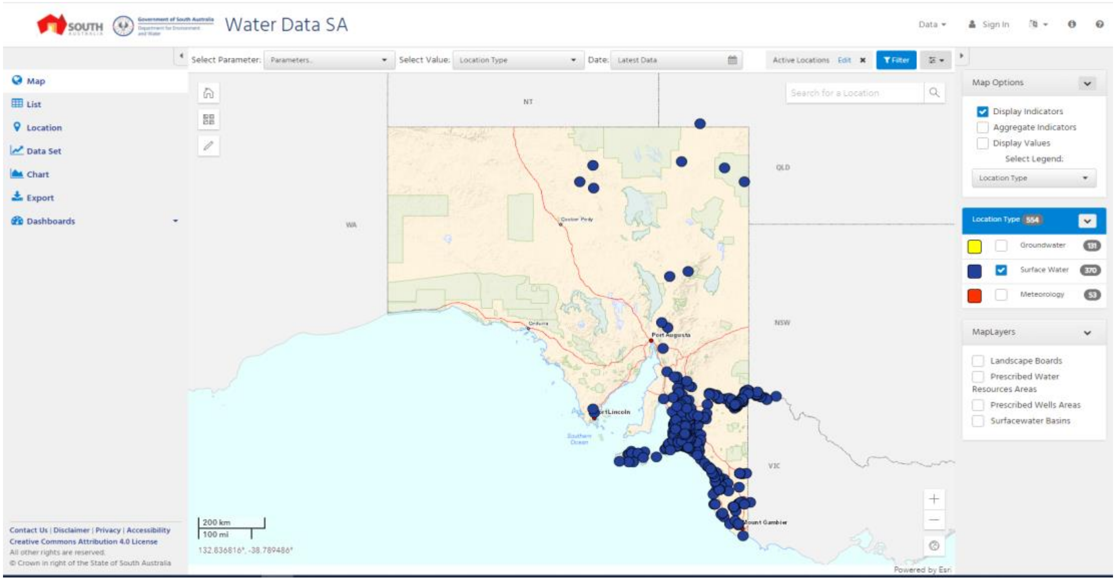


Figure 45. Portal showing near real-time water information in South Australia.

Akin to other water dashboards, this portal has different layers such as Map, List, Location and Data Set to illustrate various information. For example, the map view layer shows various stream flow stations in circles. When the required parameter, say 'Water Level' from the 'Select Parameter' tab, the details about the same are displayed in a box as shown in Figure 46. And when the 'Data Set' tab in the box is selected, a graph showing the time series of water level at that location is displayed.

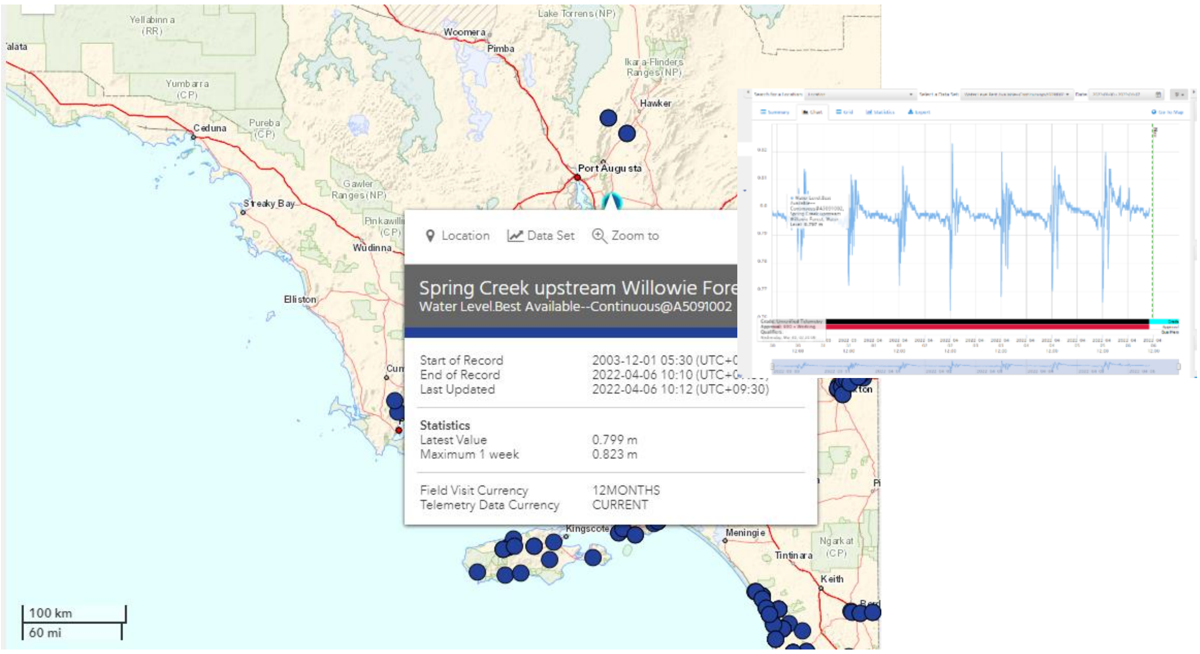


Figure 46. Image of the water portal showing water level at a station and time series water level data.

The pop-up window as in figure above shows start and end of record and last updated date. It also shows a few vital statistics.

5 Conclusions and recommendations

By incorporating the knowledge and experiences gained from the implementation of the Procedures for the Maintenance of Flows on the Mainstream (PMFM), literature review and international case studies, this report provides a comprehensive understanding of the diverse methods and approaches employed in river monitoring. The insights gained can inform the development of effective and context-specific river monitoring strategies, enhancing our ability to assess and manage the health and dynamics of the Mekong River systems more efficiently.

5.1 The Member Countries' guidance on implementing the PMFM

The national consultation meetings on updating the flow framework for the PMFM provided useful feedback for revisiting flow thresholds and methodologies. The outcomes highlighted the priorities and directions identified by the Member Countries, contributing to the development of an appropriate framework for the monitoring and planning purposes.

This collaborative process ensures that the flow framework is tailored to the specific needs and requirements of the Lower Mekong Basin, promoting effective and harmonised implementation of the PMFM across all Member Countries.

Key recommendations include data verification, whole year reporting, rapid water level variation, and the use of existing threshold methodologies. Stakeholder engagement, validation of simulated flow, and consideration of hydropower cascade impacts were also suggested. Moreover, it is critical to align the flow framework with emergency plans of water infrastructure, establish suitable thresholds at tidal stations, and prioritise capacity building.

5.2 Commonly used hydrological indicators

While these findings offer valuable insights, it is essential to note that further investigation and analysis are necessary to understand the complexities and nuances of each parameter when applying to real datasets of the Mekong mainstream and Tonle Sap Lake.

From an extensive review of the peer-reviewed scientific articles, some indicators are commonly used across studies to analyse and compare flow variations over a range of temporal scales. They are identified and listed below for possible adaptation in the Mekong context. These are seemingly simple indicators and do not involve complex calculations.

- **Mean flow** for a month, season, year or day of the year is the average flow for the period of interest and is calculated by dividing the sum of daily flows by the number of daily flows recorded for the year. This is a hydrological indicator used commonly to represent and compare flow magnitudes. In addition to the mean flow, there are other indicators of hydrologic alteration (IHA) which are used to represent flow magnitudes. They are minimum and maximum for 1-day, 3-day, 7-day, 30-day, and 90-day durations. These indicators can be used to compare the high and low flow magnitudes for various durations across years.
- **Flow percentiles** are used to compare the magnitudes of low and high flows. For example, the 90th percentile (Q10) flow is the flow which was equalled or exceeded for 10% of the specified duration (UKCEH,2022). According to USGS (2022), a percentile greater than 75 is considered above normal, a percentile between 25 and 75 is considered normal and a percentile less than

25 is considered below normal. Based on the long-term flow trends of Mekong, suitable flow percentiles may be selected to set flow thresholds.

- **Baseflow** is defined as the streamflow component contributed by subsurface storage and it sustains the river flow during dry seasons and droughts (Bloomfield et al., 2021). Knowledge and information about baseflow are critical to separate the streamflow hydrographs, especially to know the surface flow contributions before and after hydrologic alterations. This is important in the context of identifying the causes of drought in the Lower Mekong Basin (LMB) during 2019-2020. Also, baseflow trends can be used to identify unsustainable catchment management practices (Kelly et al., 2019).
- **Baseflow Index (BFI)** is the ratio of baseflow to the total streamflow and it gives an indication of the contribution of sub-surface flows, mainly groundwater to the river flows. Many of the above-mentioned papers used BFI as an indicator for flow monitoring.
- **Flow Duration Curves (FDC)** can be used to compare the flow thresholds between two periods. Aspects of FDC such as FDC slope can be used to indicate the rate of change of flows. Concepts such as ecostatistics (ecodeficit and ecosurplus) can be calculated using FDCs related to different periods and thus evaluate the impacts of river regulations. In the Mekong context, FDCs can be used to compare the exceedance values of flows between months, seasons or years.
- **Rise and fall rates** indicate the rate of change of flows and river levels. Rise rate is the mean rate of positive changes in flow or level from one day to next. Fall rate is the mean rate of negative changes in flow or level from one day to the next. The unit of rise and fall rate indicator is m/d. The rise and fall rates of two periods (for example, pre- and post-commissioning of dam) can be compared to inform the changes in flow or level.
- **Rising and falling limb densities** are also indicators used to measure the rate of flow or level change. As mentioned earlier, they are ratios of the number of rising or falling limbs to the total time of rising or falling limbs. The recent patterns of rising and falling limb densities can be compared with that of long term or pre-development ones to evaluate changes if any.

Furthermore, the following indices are correlated to catchment-specific characteristics such as climate, topography and vegetation. They are helpful in identifying the drivers of streamflow hydrographs.

- **Number of fluctuations/reversals** is a metric showing the number of positive and negative changes in water conditions from one day to the next.
- **Frequency of low and high pulses** shows the number of low flows (usually < 25th percentile discharge) or high flows (usually > 75th percentile discharge) in a year.
- **Duration of zero, low and high pulses** presents the number of consecutive days with zero, low and high flows. The low and high flow thresholds are set based on the site-specific characteristics.
- **Spell analysis plots** illustrate the frequency and duration of flows above or below a threshold value. Such plots can be part of the MRC flow monitoring tool to show the duration of a high or low flow per year for a period of record.

5.3 Inspiration for water dashboard design

The web-based tools and dashboards reviewed in this report provide valuable insights that can be adapted to enhance the design of the Mekong water dashboard. Platforms like the **USGS WaterWatch** offer a straightforward approach, enabling users to access multiple features from a single page. The

USGS National Water Dashboard also provides a comprehensive platform that presents the current flow status compared to historical flows.

The recent update of the MRC landing page brings a more unified visualisation, improving communication with stakeholders. However, the web pages for the main products and services are spread across different sites, creating a fragmented user experience. More specifically, the near real-time hydrometeorological monitoring page displays in map and list formats. Selecting a station provides detailed information, including hydrographs and rainfall trends. Other MRC webpages present flood and drought information and forecasts, while the PMFM webpages is illustrated on a separate website. It would be advantageous to have a single, comprehensive flow monitoring dashboard that consolidates all flow information and facilitates easy navigation.

Drawing inspiration from the flow frameworks of other organizations, particularly the USGS WaterWatch dashboard, selected features can be integrated to illustrate the flow frameworks for the MRC. By exploring technology adoption options, the MRC can prioritise simplicity and ease of future maintenance and operation, avoiding unnecessarily complex processes.

5.4 Way forwards

Moving forward, the activity will embark on the following steps

- **Gathering country's perspective on PMFM thresholds**: The activity will continue to engage with the Member Countries to understand their perspectives on updating the PMFM thresholds. This feedback will be valuable in guiding the refinement of the thresholds.
- **Refinement of the list of parameters**: The report will be revised to present the information concisely. Input from the Member Countries are sought to ensure the report accurately reflects their perspectives and feedback. The MRC Secretariat will further develop and refine the list of parameters to be used in conjunction with the Mekong dataset. This step will ensure that the selected parameters are appropriate and relevant for the specific context of the Mekong region.
- **Initial design of a web-based tool for Mekong Flow Monitoring**: An initial design of a web-based tool will be drafted to facilitate data visualisation and analysis. This tool will provide a user-friendly interface for accessing and interpreting the information related to the flows on the Mekong River system. Additionally, the activity will explore the potential integration of the tool with the upgrade of the Decision Support Framework (DSF), enhancing its capabilities and functionality.

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