

Integrated System for Multi-Usage Reservoir Management in Sri Lanka

Système intégré de gestion de réservoirs à usage multiple au Sri Lanka

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Abstract. The Mahaweli Authority of Sri Lanka (MASL) is responsible for planning the water allocation across five major River systems in Sri Lanka. This includes providing water to the 15 major hydro plants and over 32 irrigation areas. MASL has been using computer models since the 1980's to meet the various water demands over the entire system and establish the right balance between the multiple stakeholders as part of the calculation of a seasonal plan (SOP). This includes an evaluation of the risk associated with water shortages for irrigation. As part of an on-going modernization effort, a fully integrated system for multi-use reservoir management (Vista DSSTM) has been developed and implemented to help produce the seasonal plan on an operational basis. It includes a multi objective long and short-term optimization model, extensive data acquisition capability as well as inflow and irrigation water demand forecasting. The system has been designed to dynamically address changes in conveyance maximum capacities due to outages or other unplanned maintenance activities, along with changes in water supply due to expected near-term rain events. The new implementation has been in operation over the last 12 months and is expected to provide greater flexibility in conducting the various analyses, promote higher data integration, and further optimize the use of the country's water resources.

Résumé. La Mahaweli Authority of Sri Lanka (MASL) est responsable de la planification de la répartition de l'eau dans les cinq principaux systèmes fluviaux du Sri Lanka. Cela comprend l'approvisionnement en eau des 15 principales centrales hydroélectriques et de plus de 32 zones d'irrigation. MASL utilise des modèles informatiques depuis les années 1980 pour répondre aux diverses demandes en eau sur l'ensemble du système et établir

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un juste équilibre entre les multiples parties prenantes dans le cadre du calcul d'un plan saisonnier (SOP). Cela inclut une évaluation du risque associé aux pénuries d'eau pour l'irrigation. Dans le cadre d'un effort de modernisation en cours, un système entièrement intégré de gestion des réservoirs à usages multiples (Vista DSSTM) a été développé et mis en œuvre pour aider à produire le plan saisonnier sur une base opérationnelle. Il comprend un modèle d'optimisation multi-objectif à long et à court terme, une capacité étendue d'acquisition de données ainsi que la prévision des débits entrants et de la demande en eau d'irrigation. Le système a été conçu pour prendre en compte de manière dynamique les changements dans les capacités maximales de transport dus à des pannes ou à d'autres activités de maintenance non planifiées, ainsi que les changements dans l'approvisionnement en eau dus aux événements pluvieux prévus à court terme. La nouvelle mise en œuvre est opérationnelle depuis 12 mois et devrait offrir une plus grande souplesse dans la réalisation des différentes analyses, favoriser une meilleure intégration des données et optimiser davantage l'utilisation des ressources en eau du pays.

1 Introduction

Sri Lanka has a vast network of rivers, lakes, reservoirs and hydraulic canals that have been developed over thousands of years. It was recognized very early on that the high tropical precipitations received during the monsoon seasons could be stored and used during the drier periods. Furthermore, such waterways can move the water from areas where precipitation is more abundant, more specifically in the mountains of the central region, to drier areas at lower elevation and typically closer to the coast, thus increasing the country's capability to produce food at a large scale.

Sri Lanka is a large producer of agricultural products, growing various varieties of rice and dry crops. As a result, a significant amount of water is used for irrigation. In addition, the country is also a large producer of hydro-electric power, which accounts for nearly 30% of its energy demand, with 15 major plants and a total capacity of about 1400 MW. New hydro plants have recently been built and the system has generally been expanding over the years.

The Mahaweli Authority of Sri Lanka (MASL) is responsible for managing the water of four major rivers, including the Mahaweli, Kelani, Walawa and Kalu rivers. The Mahaweli River is the largest waterway in the country, originating in the high mountains near the city of Nuwara Eliya, and flowing north and east through a set of diversions while providing water to most hydroplants as well as to over 30 irrigation areas in the lower regions. This is illustrated in Figure 1 below.

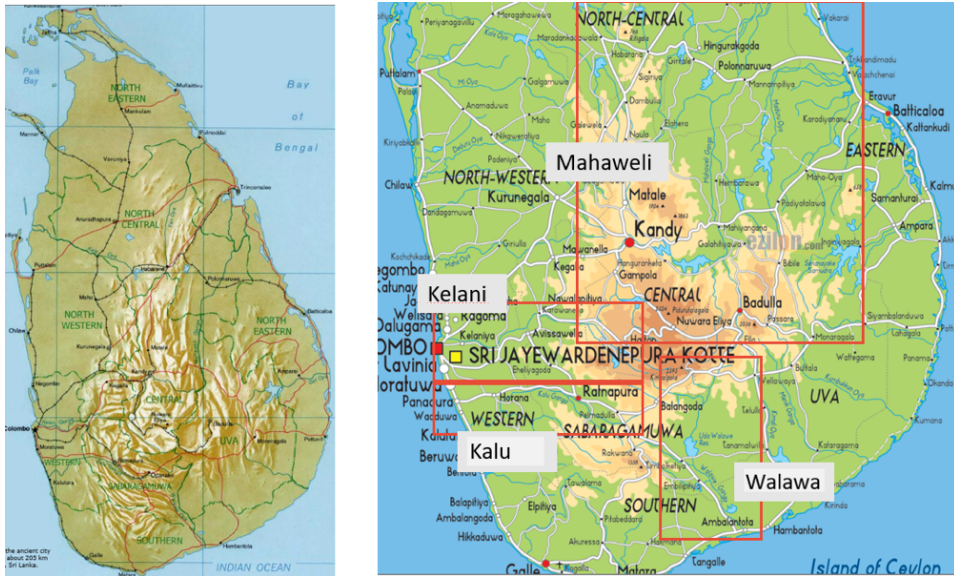


Fig. 1. River systems and irrigation areas managed by MASL.

The water management is multi-objective, i.e., with a primary consideration for providing sufficient water for agriculture while maximizing hydro generation. With the growing need to produce food, MASL is often confronted with the situation where the total amount of water is not sufficient to meet all the water requirements. It must make significant decisions on how to distribute the available water amongst the various stakeholders, therefore influencing which crops can be grown and at which location, and how much water can be used for hydro power.

To perform water management as fairly, carefully and effectively as possible, MASL has been using computer tools since the 1980's, where different irrigation and crop scenarios can be simulated and compared against each other to arrive at the best possible decisions in terms of reliability and stakeholders' overall acceptance of the water plan. The original software system that was implemented at the time was in need of modernisation, with only limited capability in terms of inflow forecasting, data acquisition, storage and archiving, multi-user access, etc., leading to this current development.

One of the objectives of the project was to provide a system that can conduct all aspects of the planning process, as opposed to having separate analyses on different tools that would be ultimately assembled into a single reporting system. Sri Lanka has also a diverse topography with a large hydraulic system, and a key operational challenge is to collect and centralize the data from the various sources.

2 MASL Water Management Planning and Scheduling Process

2.1 Long term Planning

The basic work process for long term water management consists in providing the best possible distribution of water for a given crop selection over the next season or year, while considering the various uncertainties in precipitation and natural inflows, and the balancing

and optimization of the hydro generation to meet the country’s demand. This is done on a regular basis with the production of a seasonal plan (SOP) at a six-month interval. The main steps are outlined below (see Figure 2).

- Updating of the system for the latest conditions, including
 - Actual water level and precipitations
 - Flow volumes and energy generation
 - Planned outage of hydro plants and canal diversions
 - Projected load Forecast
- Updating of the long-term future meteorological conditions, including precipitation and evaporation
- Calculation of the long-term water demand based on selected crop types
- Calculation of the hydrologic conditions based on the new meteorological data
- Simulation of the water plan
- Water supply reliability analysis
- Generation of a Seasonal Water Plan. The process is iterative until the various reliability criteria have been met

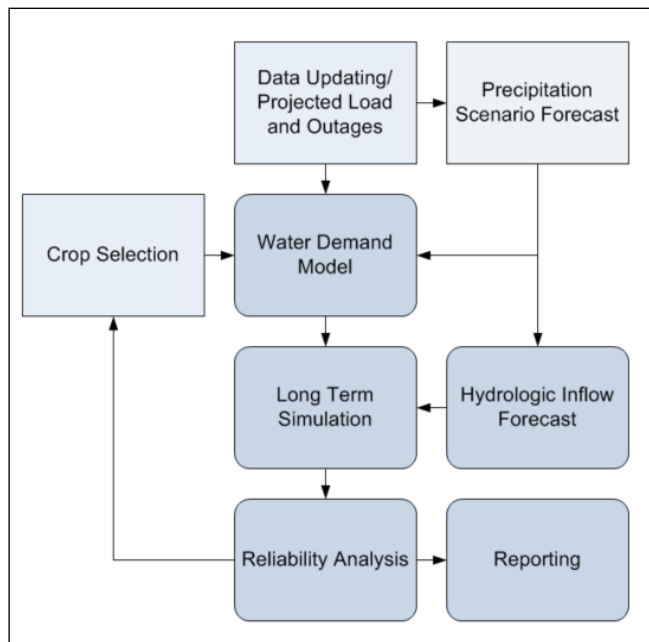


Fig. 2. Water management planning process.

2.2 Short-Term Water Management

Many factors may contribute to actual deviations from the long-term water plan, including changes to the natural inflows from what was initially predicted affecting water availability for hydro power and irrigation demand, changes in energy requirements, or simply short-term changes to the irrigation requirements. The process is similar to the long-term planning, but with a reduced number of steps i.e.,

- Updating of the system for the latest conditions, including
 - Actual water level and precipitations
 - Latest outages of hydro units and canal diversions
- Updating of the short-term hydrology

- Updating of water demand for latest changes based on weekly irrigation reassessment
- Short-term simulation of water plan with typical duration of between 3 and 14 days
- Reporting

3 System Development

3.1 Foundations of the New System

To perform the long-term water management function, a set of software models was implemented in the mid 1980's under the Mahaweli Water Resources Management project (that be subsequently referred to as the legacy system), which had been in operation since that time. It consisted of three main components, namely:

- A water demand model for irrigation
- A long-term simulation model
- A reporting and archiving system

It should be noted that the legacy system did not have a short-term planning function and had no capability for interfacing with other data sources or to automatically acquire data. The archiving was handled through a set of files and there was no centralized data repository. The reporting function was fairly comprehensive, however, it was designed for the conditions that were present at the time and offered only limited flexibility in terms of format changes and type of information to be selected. However, the most significant limitation was related to the fact that the models used an obsolete operating system and could not be easily converted to be used within a modern digital environment.

To deal with these limitations, an integrated water management system under the name *Vista* Decision Support System (*Vista DSS*TM) was deployed to replace the legacy system. One attribute of this new system is that it can integrate all the functionality required for the planning process into a single entity, sharing the information via a common database and performing the various functions via modules that can be launched individually while using the same data sources. It can perform all the various analyses both on the hydraulic and generation side, including: water demand forecasting, inflow forecasting, long-term planning, short-term scheduling, energy projection of the various energy sources to meet load, reporting and data acquisition and archiving. This is illustrated in Figure 3 below.

The main analytical functions of the integrated system are based on the same foundation as to that of the legacy system, which facilitates user acceptance and usability. However, the models have improved considerably and are generally more flexible and computationally efficient. There is also additional capability in terms of data processing and reporting, with greater emphasis placed on optimization versus pure simulation.

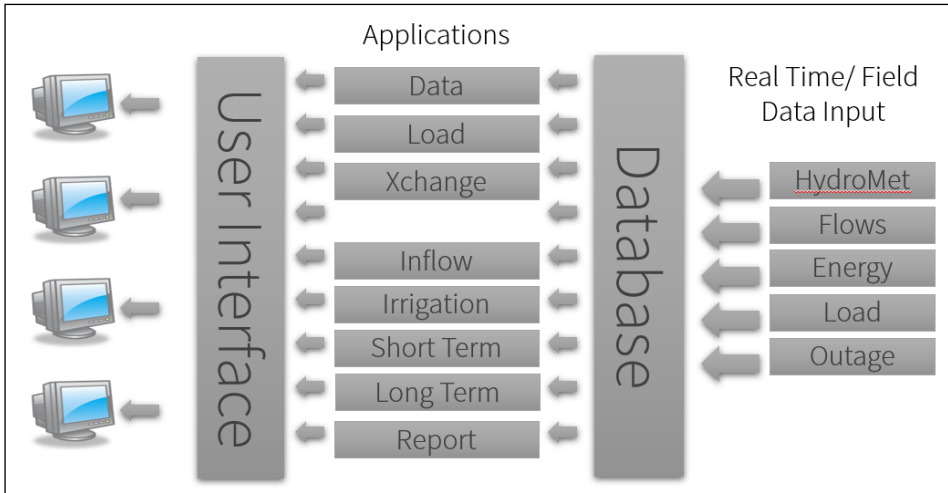


Fig. 3. Vista DSS™ Integrated system.

A comparison between the new integrated system, and the legacy system is shown in Table 1 below.

Table 1. Comparison between new and legacy system.

System Requirements	Description	Legacy System	New System (Vista DSS™)
Water Demand Planning	Seasonal Plan for agriculture	Acres ¹ AIM application	Irrigation Vista
Inflow Forecasting	More accurate forecast of available water	Historic inflows, free software for long term	Inflow Vista
Long Term Planning	Integrated seasonal plan for both power and irrigation	Acres ¹ ARSP model	LT Vista
Short Term Planning	Review and adjust plan on a weekly basis	None	ST Vista
Data Integration and automation	Hydrometric data to be collected from the various stations with automatic download capability	Manual entry into Acres ¹ DERS system	Service application
Data Storage and Archiving	Storage of all inputs and outputs	Filing system	Database
Reporting		Acres ¹ DERS system	Embedded within various modules

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3.2 Data Acquisition and Automation

Water management requires a large amount of data, and many meteorological and water level measuring stations are available throughout the country. Over the years, a number of these stations have been modernized to have automatic recording capability. This process was

accompanied with the development of a centralized system (Hydro-meteorologic Management Information System, HMIS) that was set up to collect this information.

Vista DSS™ Water Management system is designed to interact with such external systems and automate the process of data acquisition as much as possible.

Therefore, it was deployed to automatically extract data on water levels and precipitations. Ideally, other information could be automated, and this could extend to acquiring information on load forecast, energy generation and hydro unit outage from power utility companies or other organizations. The process of data acquisition and automation is illustrated in Figure 4.

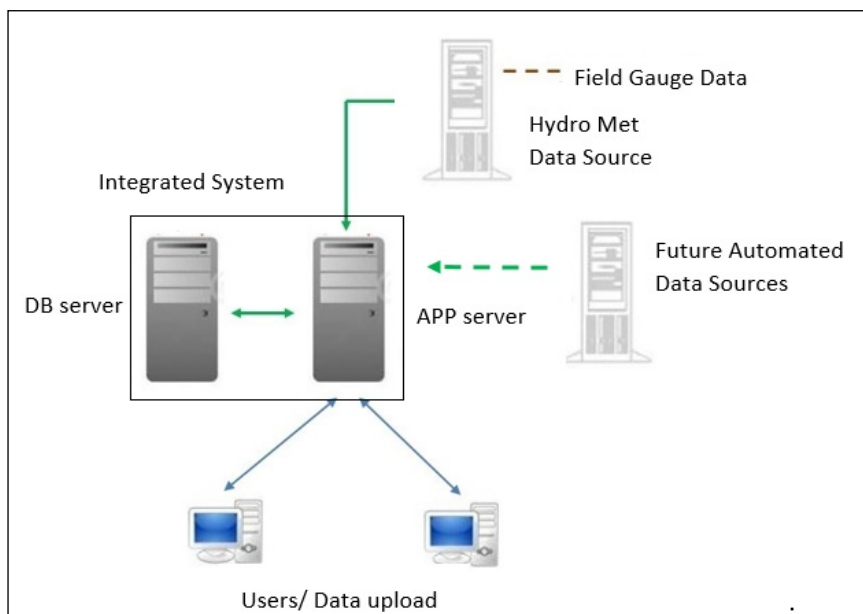


Fig. 4. Data acquisition environment.

3.3 System Enhancements and Customization

To facilitate the tasks during normal operation, some customization was brought to the system as a result of this project work, including:

- Expansion of the hydraulic network configuration functionality to include specialized arcs and nodes for irrigation. Such arcs and nodes can then be considered explicitly in the optimization/ simulation model
- Extended reporting functionality to produce the various plans associated with operation
- Integration of the Water Demand Forecasting function as one of the main modules of the deployed system, with seamless sharing of precipitation information and water irrigation demand forecast with the long-term simulation module.

4 Inflow Forecasting

Long-term and short-term inflow forecasts are required for water management of the Mahaweli system. The long-term inflow forecast is an ensemble forecast that uses historic rainfall to estimate possible future inflow series. It is used for seasonal operations planning (SOP). The short-term forecast is based on near-term weather forecast and is needed for modification of the SOP due to unplanned outages of the system's conveyances and near term expected rainfall events. Both long-term and short-term inflow forecast are grounded on the hydrological state of the basin at the beginning of the forecast as defined by real-time weather condition. Therefore, the implemented inflow forecast is an operational flow forecast system that includes the following main components.

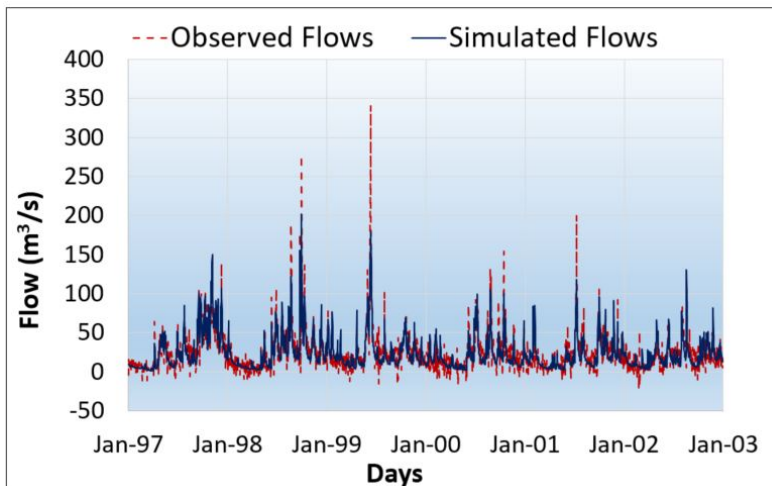
- Basin process inflow forecast model or engine.
- Real-time weather data collection and data transmission
- Weather forecasting

The inflow forecast for the Mahaweli system is implemented in two phases. The first phase covers six upper watersheds of the two largest river basins in the system, i.e., the Mahaweli River and Walawe River basin. More details are available in Table 2, Section 7.1.

To arrive at the proper modeling of the various watersheds, the following tasks were undertaken:

- Estimation of historic local natural inflow from operations data
- Selection of rainfall stations for watershed mean areal precipitation
- Inflow model calibration

More details regarding these three tasks are given in Section 7. At the end of the process, comparisons between historic actual natural inflows, and forecasted simulated inflows over a sizeable historic period were conducted and shown to provide favorable results, as illustrated in Figure 5.



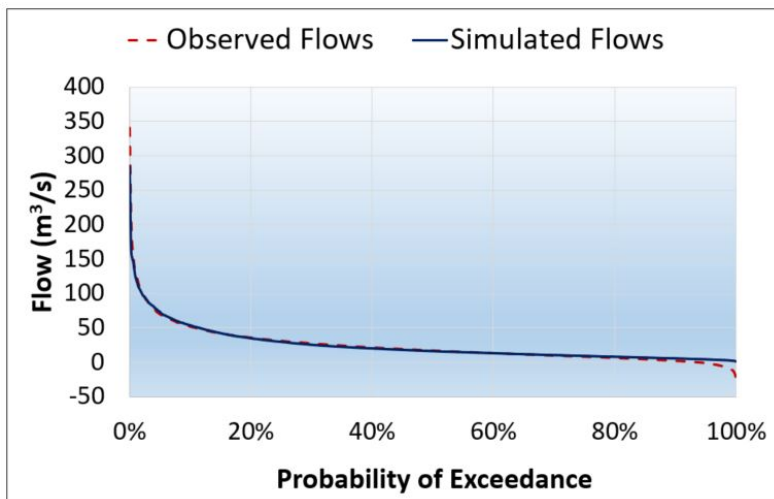


Fig. 5. Comparison between Kotmale simulated and backrouted daily flows as time series and flow duration curve.

Such calibration results should provide more accurate forecasts of natural inflows that can be used as input to the short-term and long-term simulation and optimization models for water management planning. These forecasts can also be re-calculated over time and allows for further adjustment of the Water Plan as the season progresses.

5 Long Term Water Management Planning

5.1 Hydro System Configuration

The area managed by MASL is fairly large, with over 15 hydro plants, 32 reservoirs, 32 irrigation areas, with multiple diversions and waterways forming a vast hydraulic network. Therefore, the first task was to enter the hydraulic configuration into the system. Overall, more than 150 hydraulic nodes and 300 hydraulic arcs were required to model the entire system, as illustrated in Figure 6 showing the Mahaweli River system below:

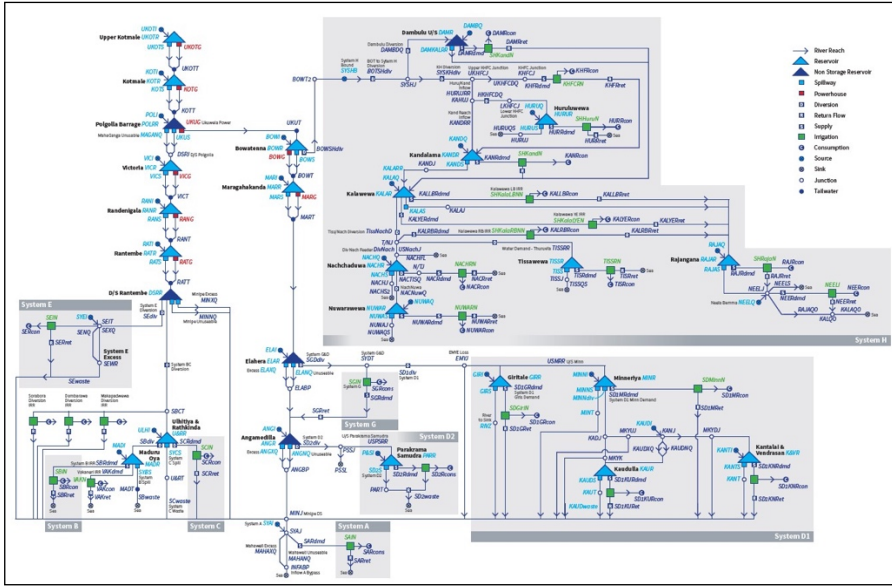


Fig. 6. Schematic of MASL river system.

It should be noted that the system configuration is user defined and could easily accommodate the various expansions of the hydraulic and energy generation taking place over time.

5.2 Energy System Configuration

The planning process requires the representation of the various energy sources in addition to the hydraulic network. The balance between the load demand and the generation produced by the hydro plants must be met by the combination of various thermal sources using various fuel types such as coal, diesel or natural gas, as well as from some independent producers called private producers, as illustrated in Figure 7.

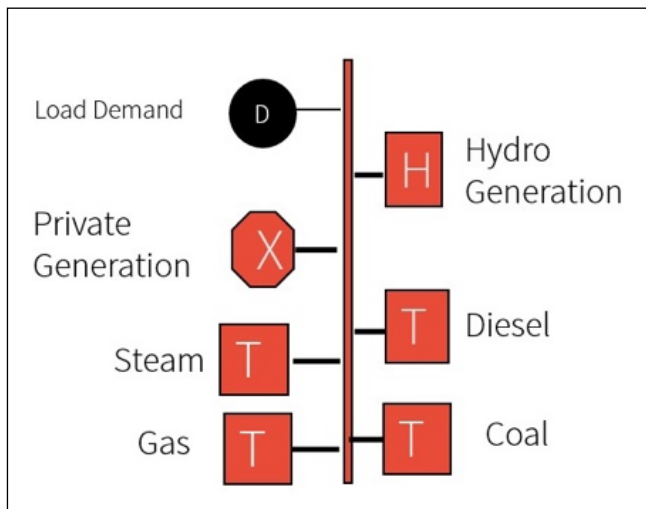


Fig. 7. MASL energy representation.

5.3 Water Demand Forecast

The process of estimating the water demand for irrigation is a very important step for preparing the water plan. Sri Lanka has two growing seasons, and a forecast must be prepared for each season. Every irrigation area is subdivided into fields for which crop types must first be specified. The concept is based on the model from the Food and Agricultural Organization of the United Nations (FAO), and calculates the irrigation water demand according to a water balance for each irrigation area where precipitation, evaporation and soil percolation are considered.

A profile of water demand is calculated over time, where requirements vary with the various phases of the crop development including land preparation, planting, growth and harvesting phases. The model also takes into consideration staggering of the crop to reflect the fact that each phase stretches over some time period. Because water demand varies with the influx of water in the form of net precipitations, an ensemble of precipitations, is used as input and an ensemble of water demand is typically calculated for analysis. Typical sets of precipitation inputs and matching water demand results from the model are shown in Figure 8, showing the demand distribution over time (March to September Yala season).

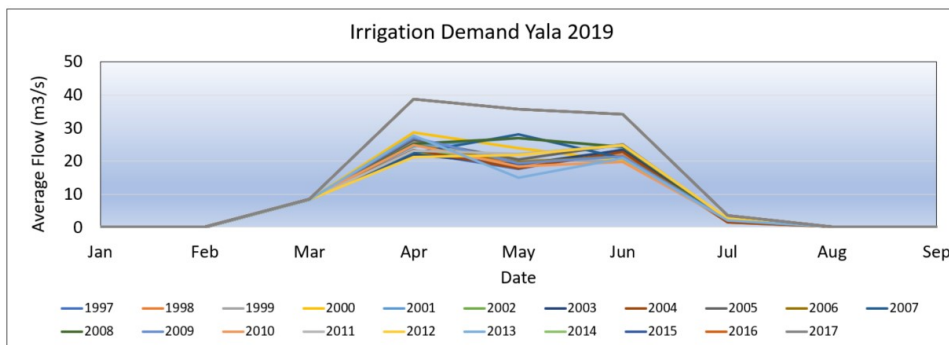


Fig. 8. Typical water demand per month for different sequences (March to September season).

It should be noted that the same model can also be used to update the evapo-transpiration for the various irrigation areas based on a standard approach (Penman-Monteith methodology).

5.4 Long-Term Simulation

The long-term water plan considers the uncertainty of the water supply by analyzing an ensemble of natural inflows and water irrigation demands. Both are tied through the definition of future years, which is a key concept in the integrated system. Many future years can be considered in the model. MASL has typically limited its analysis to the last 30 years of historic precipitations, with matching natural inflows and irrigation demand values.

The long-term model can be used in optimization or purely in simulation mode. It uses a non-linear successive linear programming approach (SLP) to solve for the combined hydraulic network and transmission system linking the various energy sources, including all hydro plants and thermal sources (Figure 9).

The use of multiple scenario analyses for various time series of natural inflows permits the calculation of the water plan based on the following key inputs:

- Natural Inflows
- Water Demand for irrigation
- Energy Load demand
- Long-term planned outage, including hydraulic structure diversions and hydro units
- Reservoir operating rule curves
- Initial reservoir water level

A typical analysis is conducted over one season at a monthly time step. However, the system is fully flexible in terms of time resolution and study period. The model produces as many trajectories as there are defined future cases. The results are statistically analysed within the application and are presented as a probability of exceedance. Because MASL is mostly concerned with the dry years, the average expected trajectory as well as dry 80% probability of exceedance are typically reported. This is illustrated in Figure 9:

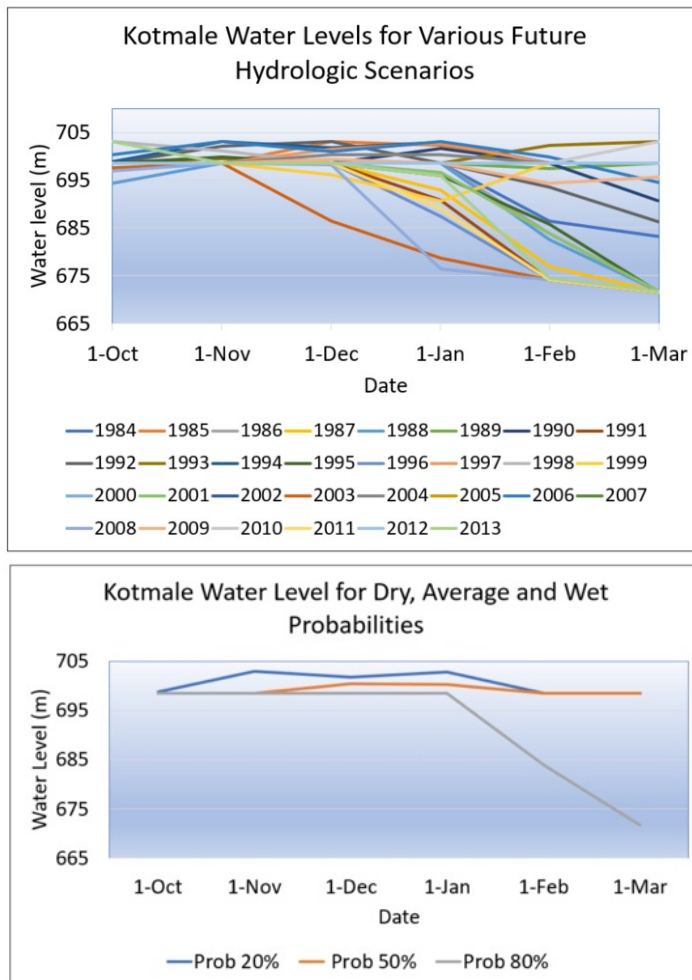


Fig. 9. Variation in water levels at Kotmale reservoir showing: (a) all hydrologic sequences; (b) 20, 50 and 80% exceedance.

Similarly results can be obtained for calculating the energy mix and the contribution from the various hydro, thermal and independent plants, where more hydro power generation can be expected during wet years, and vice versa for the dry years (Figure 10).

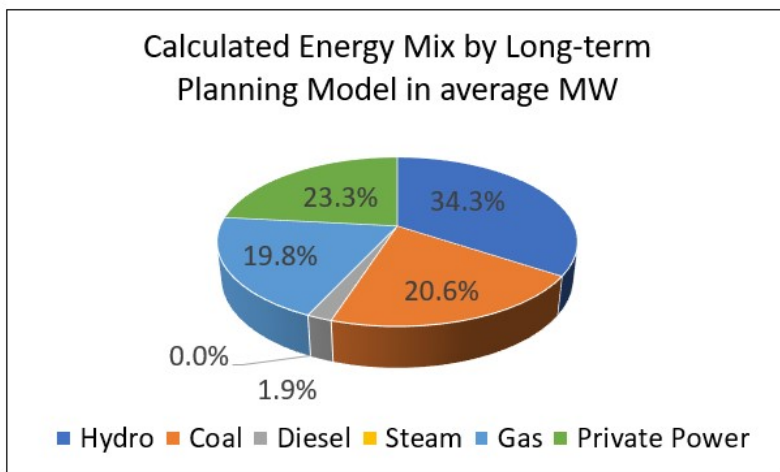


Fig. 10. Example of calculated energy mix.

6 Short-Term Water Management

The short-term model uses a similar system representation as that of the long-term model, however it operates with an hourly time resolution over a short period of time. It also considers short-term inflow forecast and operates according to the reservoir targets set by the long-term plan. With a more precise view of the hydrologic inflows, its main role is to help make decisions on water re-allocation as the season progresses and more accurate information on the current conditions and hydrologic forecast is available.

7 Development of the Hydrologic Model for Inflow Forecasting

7.1 Estimation of Historic Daily Natural Inflow from Operations Data

There are no direct flow measurements for the six modelled watersheds. Daily natural local inflows to the forecast points are derived from historical generation plant power flows, reservoir spill flows, diversion flows and storage changes (as indicated by water level changes) and upstream storage outflow. The procedure is typically referred to as “back-routing” where estimates of historical inflow to the project are based on simple mass balance between inflow, outflow, and changes in reservoir storage.

Operational records used for the flow derivation include storage, spill, power, diversion and irrigation conduit flows, as well as sluice issues. The available data cover different periods at different locations. Daily natural inflows were derived for the period of available data at each location. Summary statistics of the backrouted flows are presented in Table 2. As typical of backrouted flows, the estimated inflows include some negative values. It will also be noted that estimated flows for three of the watersheds include very large negative

values and extended periods of negative inflows with percentages of time where flow is negative ranging from 21.5% to 49.4 %.

Table 2. Summary Statistics of derived daily local natural inflow.

Watershed Name	Drainage Area (km²)	Period	Max Flow (m³/s)	Min Flow (m³/s)	Average Flow (m³/s)	Time Flow<0 (%)
Kotmale	572.9	May-85 to Feb 2017	465.98	-53.48	26.21	5.8
Polgolla	776.5	May 1985 to Feb 2017	1,328.43	-49.62	34.06	8.1
Victoria	550.7	Sep 1984 to Feb 2017	747.31	-450.31	14.12	32.0
Maduru Oya	471.9	Oct 1985 to Feb 2017	816.98	-638.34	8.12	49.4
Samalanawewa	320.0	Sep-92 to Feb 2017	604.00	-243.4	18.03	21.5
Udawalawe	823.1	Apr-90 to Feb 2017	322.83	-51.06	14.04	8.8

7.2 Selection of rainfall stations for watershed mean areal precipitation (MAP)

Rainfall is the key input to a hydrological process model for a tropical region such as Sri Lanka. Historic rainfall data is needed to configure and calibrate the model. A review of available rainfall stations was conducted to identify the ones located in the vicinity of the study watersheds. Seventy-four stations were identified and their daily historical records in the same period as the available historic flow records, i.e., 1984 to 2017, were acquired for further review. Some of the stations have been discontinued and a number of them have many missing periods. Therefore, only the 29 stations, each having not more than 60 days of missing records in any year, were selected for MAP estimation and inflow model calibration. The selected stations and their locations in the basin are shown in Figure 11.

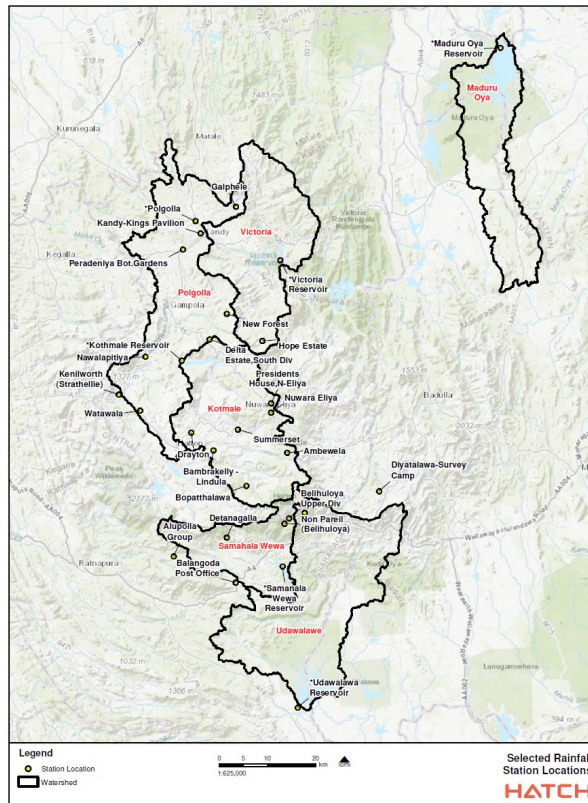


Fig. 11. Location of rainfall stations selected for inflow modelling.

7.3 Inflow Model Calibration

The calibration of the Mahaweli watersheds is a basin process that consists of a suite of models included in the National Weather Service River Forecast System (NWSRFS) for forecasting of natural inflows. Two components are used:

- Sacramento Soil Moisture Model (soil moisture accounting and runoff determination, Burnash, 1973)
- Watershed routing model

Calibration requires a historic data base of sufficient length to calibrate and verify the model for a range of hydrologic conditions. A minimum of a 20-year history of both rainfall and streamflow data is generally needed. The data is divided into a calibration set (about 2/3 of the available data) years and an independent verification set (the remaining years). In order to capture the underlying hydrologic process as best as possible, the approach adopted was to use only periods with relatively higher quality data, free of extended periods with negative values, for calibration and verification. The periods with the best quality data were selected for calibration, and periods with the next best quality data for verification.

The calibration of the NWSRFS equations is a multi-step process including the use of automatic parameter search techniques to arrive at a set of parameters that optimizes goodness of fit criteria. Finally, simulations are done using the calibrated parameter set and verification data set, to verify that the model performance for the verification set is similar to what was obtained during calibration.

The Inflow Vista module allows for model time step lengths from 1 to 24 hours. The time step employed for each watershed is selected based on the size and response time, and the rainfall data time step. A 24-hour time step was selected in this study as rainfall data is available in daily time steps.

As with any watershed modeling, the accuracy and reliability of the results are determined by how representative the model is of the catchment and by the quality of the meteorological and streamflow records used. NWSRFM has been applied successfully to thousands of catchments with different climatic and hydrologic characteristics. However, an important challenge of this project has been finding periods with good quality data for calibration and verification.

7.4 Calibration and Verification Results

Flow forecast models are commonly evaluated based on several statistical metrics. For this project, three metrics are computed for evaluation purposes. These are Coefficient of Determination (R^2), Root Mean Square Error (RMSE) and Average Error. However, these metrics are more efficient for data with non-negative flows. R^2 and RMSE are more influenced by extreme flows which are likely to have the larger errors in the estimated flow. Additionally, the large negative flows will adversely affect the R^2 and RMSE values and the Average Error, in the case of systematic biases. Therefore, visual closeness of the observed versus modelled hydrograph is also examined. In addition, duration curves of the observed and simulated flows are visually compared.

The model evaluation statistics are presented in Table 3 and a sample graphical comparison of the simulated and backrouted flows for the calibration period for Kotmale was shown in Figure 5. The results indicate that the performance was good, especially considering the quality of the backrouted flow.

Table 3. Calibration and verification evaluation statistics.

Watershed	Calibration				Verification			
	Period	RMSE (m ³ /s)	R ²	Avg Err (m ³ /s)	Period	RMSE (m ³ /s)	R ²	Avg Err (m ³ /s)
Kotmale	1997 - 2016	13.73	0.75	0.12	1987 -1996	21.60	0.58	-1.51
Polgolla	2005 - 2016	26.22	0.73	0.07	1999 -2004	17.35	0.60	-3.92
Victoria	1990 - 2000	29.51	0.30	-1.45	2002 -2003, 2006 – 2009 and 2013 – 2016	32.68	0.27	-8.46
Maduru Oya	2002 – 2010 and 2012 - 2015	25.15	0.57	-1.53	1989 - 1996	21.87	0.46	-1.67
Samalana-wewa	2001 - 2016	9.48	0.65	-1.88	1993 - 2000	13.33	0.50	2.13
Udawalawe	2005 - 2016	28.74	0.50	-0.10	1995/96 and 2001 - 2004	22.67	0.42	-0.83

8 Conclusions

The deployment of the new water management system provides an integrated environment for conducting all the main tasks involved in the water management planning and scheduling process at MASL. It allows for greater data automation and storage capability, increased accuracy in terms of the projected water supply through well calibrated and integrated hydrologic models. The planning models are based on a rigorous optimization approach aimed at considering constraints and rules of operation while meeting energy requirements at least costs.

Further work should include completing the calibration of the system's inflow forecasting module to all watersheds, as well as expanding the activities on data integration so that the latest hydrologic and operational information can be included in both the long-term planning and short-term term analysis.

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