River-flood forecasting methods: the context of the Kelantan River in Malaysia

M Abdul Majid1*, M Hafidz Omar2, M Salmi M Noorani3 and F Abdul Razak4

1,3&4 School of Mathematical Sciences, FST, Universiti Kebangsaan Malaysia
2Dept. of Mathematics & Statistics, KFUPM, Dhahran, Saudi Arabia

* Corresponding E-mail: abdulmajid_2000@yahoo.com

Abstract. River-flood forecasting is among the most important feasible non-structural approaches used in reducing economic losses and alleviating human sufferings. In spite of uncertainty in the forecasting of natural disasters, the current prevailing methods developed in many parts of the world in the recent history has made good progress to a great extent. The advancement is attributed mainly due to the availability of high-resolution weather data and the use of sophisticated computer modelling algorithms. However, it is desirable to conduct exploratory review studies to further improving the current state of affairs. The present paper reviews briefly the river-flood forecasting methods currently used worldwide with a specific focus in the context of the Kelantan River in Malaysia. Flooding in Malaysia is recurrent covering a large inhabited area compared with other natural disasters. Some of the popularly used methods in the literature such as statistical methods, machine learning and methods based on chaos theory have been reviewed. The paper will also attempt to explore the future direction for research and development that might be useful specifically for dealing with the recurrent rivers flooding in Malaysia. A reasonably acceptable prediction of river streamflow is significantly important in disaster management and water resources management.

Keywords: Rivers flooding, forecasting methods, review, Kelantan River Malaysia

Track Name: Land, Water, forest and food security

1. Introduction

The Inter-Governmental Panel for Climate Change (IPCC) [1] and the United Nations Office for Disaster Risk Reduction, (UNISDR) [2] reports state that flooding is ranked as one of the most frequent, destructive and damaging natural disasters. The catastrophic disasters that have been reported between 1990 and 2019 make up about 90 % out of 1000 [3]. It further states that, because of these disasters, only in the year 2018 about 6500 have lost their lives reportedly and the livelihoods of over 57 million people have been affected with an economic loss of over US$ 140 billion worldwide. Floods record 43 % of most registered events between 1994 and 2013 consequently affecting about 2.5 billion people [4]. It is believed that such occurrences are on a steady rise [5] and in Malaysia this is happening mainly because of the annual monsoon rainfall. There is an increasing trend of several flooding in tropical regions. Malaysia’s location near the equator mainly makes its climate hot and humid throughout the year. It has experienced several floods recorded as far back as late 1980s. The floods in Malaysia are a regular phenomenon and they occur during monsoon seasons. They affect the socio-economic structure
immensely affecting a large inhabitants and disruption to normal life. In spite of several mitigation measures put in place by the government of Malaysia, the country has witnessed a long history of this natural disaster. No country is safe from extreme natural events. There is no foolproof method for completely avoiding it no matter how sophisticated and advanced tools and systems we develop for controlling it and the current measures are only partially successful.

Floods are classified as river floods, mud floods, dam floods and flash floods etc. A river flooding mainly causes due to heavy incessant rainfall over a short period exceeding the capacity of soil absorption. A flood is caused by above normal streamflow, leading to inundation of areas, which are normally not covered by water, as it is mainly restricted to abrupt change in high streamflow levels. The floods in Kelantan basin, occur in December frequently and with a high magnitude. Kelantan, northeastern region of Peninsular Malaysia, has an area of 15,099 km² and surrounded by Thailand, Perak, Pahang and Terengganu and a map of the river is given as figure 1 [6] and its characteristics in Table 1.

Table 1. Characteristics of Kelantan River.

| Length   | Catchment Area | Land use tributaries | Observation Station | Mountain (peak) |
|----------|----------------|----------------------|---------------------|-----------------|
| 248 km   | 11,900 km²     | Galas River, Lebir River | Guillemard Bridge   | Korbu 2183 m    |

River flow forecasting plays a vital role in controlling extreme hydrological events. Forecasting is an estimation and hence it is quite a tricky endeavor as it involves modelling errors, with a lot of uncertainty and nonlinearities involved in the process. The purpose of developing a flood early warning detection system is to reduce the risks and dangers and to prevent from the hazards of flooding. The real time precipitation data [7] and [8] and numerical prediction models [9] are considered two important
factors in the development of flood early warning system. Moreover [10] has emphasized the importance of flood-disaster management actions and identified the development of an effective early warning system as an important milestone for the vulnerable world population by 2030.

The predictive hydrological and hydraulic modelling of the river flooding, though highly complex, but it is considered largely feasible with the current computational tools such as digital elevation models (DEM), and geographic information system (GIS), as they are believed to provide high accuracy in improving flood forecasting [11]. The non-structural early warning and alert systems can be developed based on forecasting of a river flow. In this study, a review of studies is undertaken on various forecasting methods and the focus is the Kelantan River only.

1.1. Models’ Classification

The scientific studies of extreme hydrological events and natural disasters such as floods pave a long way in understanding the complex dynamics of these unusual occurrences and they are important to minimize the losses and maximize the possible benefits. It is well known that the complex behavior of natural systems cannot be accurately understood through laboratory experiments or modelling based on historical data. Nevertheless, scientists from diverse disciplines have been conducting numerous studies and there is an ever-increasing interest to have a proper control of such extreme events. Moradkhani and Sorooshian [12] describe a model as a simplified representation of real-world system. One important application of the river flow analysis and forecasts is the development of an early warning to floods.

Devia et al. [13] have classified hydrological models as empirical, conceptual and physically based. According to [14], the conceptual models take into consideration a priori structure of the model based on the perception of a hydrologist and the parameters are calibrated against the observed time series, while the physics-based models derive parameters from the field measurements and the identification of parameters must be done through inverse modelling approach. As non-structural measures for the mitigation of flooding, [15] proposed a classification of model structures and types that includes deterministic models as physics-based, conceptual and empirical and stochastic models as depicted in Figure 2. Table 2 and Table 3 use the classification as physical models and conceptual models following [16] for rivers in Malaysia.

![Figure 2: Classification of Model Structures and types](image)

2. Methodology

The resources that were used to search for the relevant articles for review have been accessed through the UKM’s online library included Scopus, web of science, IEEE, Wiley, ProQuest, Science Direct and Taylor and Francis. These resources provided e-books, conference proceedings such as the proceedings
of AICCE’19, AWAM international conference on civil engineering and ISFRAM 2014 Proceedings of the International Symposium on Flood Research and Management etc. apart from the Google Scholar and Springer Link. The search was restricted to flood forecasting methods in the context of Kelantan River during 1990 to 2021 only with a brief review of related studies in general worldwide.

The objective of this study is to review all the studies related to flood forecasting of Kelantan River, Malaysia with a brief overview of the studies conducted worldwide using methods in statistics, chaos theory and machine learning etc. The other objective is to highlight the study conducted by the authors [17] as a recent development. Finally, some future direction in research work will be provided.

3. Review of hydrological forecasting Studies

During the past few decades, the hydrological studies largely focused on the statistical methods such as ARIMA [18], SARIMA [19] including the river flow forecasting. The application of statistical methods usually establish linear and nonlinear relationships of variables using historical hydrological data. Apart from the statistical methods, several machine learning are also applied for river flood analysis and forecasting. The study of the dynamics of a river streamflow, inherently nonlinear in nature, requires the use of appropriate sophisticated methods. With the increased availability of hydrological data and the affordability of the computing capabilities, one of the popularly emerging approaches is the use of machine learning; rooted in artificial (machine) intelligence. [20] reported that these developments in data and computing could lead to changes in flood risk and impact assessment. The machine learning algorithms work on the principles of recognizing patterns in input data. These algorithms are currently used in forecasting of the nonlinear systems and there is a paradigm shift in modelling from physical based processes to the optimized data-driven modelling. Some of the known machine learning methods mentioned are Radial Basis Functions, Generalized Regression Neural Networks, Neighbor regression, CART regression trees, Bayesian Neural Network, Support Vector Regression and Gaussian Processes and Multi-Layer Perceptron, [21]. The ANN models work on historical data in contrast with the models requiring calculation of physical characteristics of a catchment. In spite of the ANN being a good potential candidate for forecasting over several statistical methods it also has some drawbacks. Some of the drawbacks include modeling overfitting error, gradient descent, slower rate of convergence, and high training data restriction. For a comparison between ANN and AR models, readers can refer to [22], [23] and [24], between ANNs and ARMA [25], [26] and [27]. The comparison revealed that the performance of ANN was superior to that of the statistical techniques. In a study by [28], the performance of SVR (support vector regression) model to predict long-term monthly flow discharge series was better than the performance of ARMA. The SVR also outperformed ANN. [29]. The short-term streamflow prediction by the phase space reconstruction method was reportedly better when compared with ANN, [30]. They have applied a combination of ARMA, KNN, ANN, MA-ANN, Phase Space Reconstruction and FNN to hydrologic time series prediction. The phase space reconstruction method and the recurrence analysis method derived from the chaos theory, based on the detection of a suitable embedding dimension and time delay, are also used as a forecasting method, [17].

Tilford et al. [32] highlighted the need for a number of factors to consider when selecting a new flood forecasting solution for a catchment or site which includes the physical characteristics of the catchment and river flow; the quality and the availability of related data; the cost and time of development; technical and economic risks associated with the investment. Furthermore, the authors have proposed that the forecasting model must meet national targets for accuracy and lead-time.

3.1. Kelantan River flow analysis and forecasting

Kelantan historically has witnessed severe floods of varying magnitude, often times, affecting its adjoining states such as Terengganu and Pahang etc. The flooding event that occurred in late December of 2014 has particularly caused massive destruction and [33] have described it as the largest ever recorded in the history of Malaysia. According to [34] report, the flood of 2014 has been the most significant largest ever recorded and termed as “tsunami-like disaster” in the history of Kelantan.
According to [35], between 14-18, December 2014, the downstream of the Kelantan river was poured and inundated due to incessant heavy rainfall. This was followed by a second spell between 21-24, December 2014 and this time it was the upstream of the river. The soil saturation caused a rapid runoff and aggravated the flooding phenomenon and it was more severe in the Kuala Krai valley. The lives of the thousands of the residents were affected and with some fatalities. This clearly demands a thorough scientific understanding of the dangers and coming up with necessary measures to mitigate and control the dangers for the ever-growing population in the area through urbanization. Some of the possible non-structural and cost-effective measures are the development of an effective functional flood early warning system and the forecast modeling. [36] have applied stochastic flood forecasting model for Kelantan River.

Abdulkareem et al. [16] provides a comprehensive review study on the forecasting models in Malaysia. The report cited the studies focused on Kelantan River comprise about a quarter of the total studies conducted in Malaysia until 2018. The authors have classified models as physics-based and conceptual models. Our paper focuses only on the studies related to the Kelantan River due to the recurrent nature of flooding and its disastrous consequences. The lists of studies related to Kelantan River have been provided in Table 2 and Table 3. The modelling performance of the reviewed studies provided in tabular forms were mainly based on the values of R, R², NSE, RMSE, MAE and PBIAS among which RMSE is notably a popular common criterion.

Table 2. Physics-based Models for Kelantan River.

| Model | Research Paper | Model Performance criteria | Study |
|-------|----------------|-----------------------------|-------|
| HECHMS | [37] | To study the peak discharge variation and their factors related to discharge and runoff volume or different return period. |
| HECHMS | [38] | To look into the causes of flooding through the study of relationship between morphometric characteristics and the hydrological factors. |
| HECHMS | [39] | Coefficient of determination (R²), NSE, percentage bias (PBIAS), mean absolute error MAE | To study variations in peak flows |
| [HEC-HMS and Transient Rainfall Infiltration and Grid-Based Regional Slope Stability Analysis (TRIGRS)] | [40] | | To assess the effect of Land use/land cover (LULU) change. |
| HECHMS | [41] | RMSE, MAE, NSE, R | To study the effects of environmental and ecological factors of watershed development and to assess flood prone areas during extreme storm events. |
| (HEC-HMS and Improved TRIGRS model) | [42] | | To study the infiltration rate and governing equation related to land cover sensitivity maps and run off volume. |
| Integrated flood analysis system (IFAS) | [43] | Coefficient of efficiency (Ec) and peak discharge error (Ep) | To determine the applicability of IFAS model. |
HECHMS [44]

To study the conditions and the type of land use and land cover on peak discharge and the volume of the runoff as well as the prominent factor resulting in maximum flows.

HECHMS [45] RMSE, R

To determine the influence of extreme rainfall on the performance of HEC-HMS model.

Table 3. Conceptual/Empirical Models for Kelantan River.

| Model                                      | Research Paper | Model Performance criteria      | Study                                                                 |
|--------------------------------------------|----------------|---------------------------------|-----------------------------------------------------------------------|
| Fuzzy logic                                | [46]           | MAE, Relative Root Mean Square Error (RRMSE), NSE and R | To study the real time river water level forecasting as a flood early warning tool. |
| Time Lag Forward Network                   | [47]           | MSE, RMSE                       | To study forecasting of water level hourly.                          |
| Empirical model (ANN)                      | [48]           | MSE                             | To forecast flood water level.                                        |
| Empirical model [Numerical weather prediction (NWP)] | [49]           | R                               | To effectively predict flood using NWP.                               |
| Empirical model [Support vector machine (SVM), frequency ratio (FR) and decision tree (DT)] | [50]           |                                  | To study the flood susceptibility mapping with the comparison of the performances of the models used. |
| Empirical model [rule-based decision tree (DT), FR and logistic regression (LR)] | [51]           | FR, LR                          | To compare the ability of DT and the combined use of FR and LR in flood susceptibility mapping |
| Conceptual model (Probability distributed model) Physically-based model (Kinematic wave model) | [52]           |                                  | To produce a flood susceptibility map.                               |
| Empirical model (Logistic regression)       | [53]           |                                  | To produce flood susceptible map of flood prone areas with the aid of a statistical model and GIS. |
| Empirical model (Logistic regression)       | [54]           | Flood susceptibility index       | To map out maximum flood prone area with the aid of multiple regression model using GIS techniques and remote sensing. |
| Neural network autoregressive exogenous input (NNARX) model | [55]           | MSE                             | To predict floods and comparison with wavelet decomposition             |
Tables 2 & 3 provide lists of hydrological modeling methods that have been applied to various rivers of Malaysia highlighting the purpose of the study. Some of the studies have used only one method and others have used a combination of methods. One of the limitations that we found in all the studies that were focused on the Kelantan River forecasting is a very important aspect of the forecasting that is the floods early warning detection system.

Among several methods, Auto-regressive integrated moving average (ARIMA) model was reportedly used in only 8% of the research studies, [16] in the context of Malaysia. Based on the review of previous studies of the use of forecasting models in hydrology, it can be seen that the method of recurrence plot and recurrence quantification analysis in combination with ARIMA has not been explored except the work carried out by the authors, [17]. Furthermore, we have not found any study in which ARIMA has been used as a forecasting method for Kelantan River. We believe that this is the second limitation observed, as a result, of the review of the related studies.

3.2. Recurrence analysis method and ARIMA method for Kelantan River flow forecasting

Firstly, an analysis of the time series data for the years 2000 to 2014 was carried out using recurrence plot, recurrence quantification and ARIMA to understand the dynamic behavior of the river flow and the indicators of early warning signs. The forecasting capabilities of these methods were also used including the highlights of the floods early warning detection indicators. [56] have put forth the concept of a recurrence plot as a qualitative visualization tool for detecting the recurrences in a dynamical system and later have provided an objective analysis through the technique known as recurrence quantification analysis. [58] have extensively applied the recurrence analysis method successfully for various dynamical systems. This technique was used for the analysis and forecasting of Kelantan river time-series data for 2000-2014 and for more details of the study, readers may refer to [17]. In addition, ARIMA model was also used for forecasting the flooding by using the year 2014 data as a holdout data. A comparison of the performance of forecasting models was also carried out between recurrence method and ARIMA. [17] provide details of the modeling information utilized. Models’ performance based on RMSE revealed that ARIMA model predicted better result. The three phases are involved in this study, namely, the model-building phase, predictive phase, and finally the recurrence quantification analysis phase. The model-building phase used Kelantan daily river-flow data prior to 2014 while the predictive phase feature performance of the chosen models on the holdout 2014 daily river-flow data. Figure 3 and Figure 4 provide the time series plot of the stream flow data for the years 2000 to 2014 and the ARIMA model of the order (5, 0, 3) respectively. A closer examination of Figure 3 and 4 shows that the maximum flow for 2014 (i.e., the flooding event) does not fit the panel for Figure 4 as the main data that build the model for figure 4 are from 2000 to the end of 2013. The maximum for the data-building phase is not nearly as extreme as the maximum of 2014 that can be seen from Figure 5.
Figure 3. Kelantan River-flow data for all years including the 2014 hold-out data. [17]

![Forecast from ARIMA(5,0,3) with non-zero mean](image)

Figure 4. Kelantan River-flow time series data (in black), hold-out data (in red) represents 2014 data, and predicted forecast values (in blue). [17]

3.3. Floods early warning detection using ARIMA:
According to [32], hydrological forecasting models play a crucial role in the development of flood warning systems. The 15 year-time series data of the Kelantan River flow is depicted in Figure 4 from [17]. The figure also contains the year 2014 data highlighted in red color, the 80 % and the 95 % confidence bands in different shades of blue, and the predicted forecast values in blue color. It can be clearly observed that most of the 2014 time series data fall within 80 % (shorter) and 95 % (wider) confidence range except at the onset, latter half and at the end of 2014. The values outside the 80 % and 95 % confidence bands can be considered as an early warning indicator that the river flow is reaching aberrant volumes and may be dangerous. These bands can be incorporated into an early warning system so that populated areas surrounding rivers such as Kelantan River can take precautionary measures as soon as these bands are breached. As can be seen from Figure 5, this band is breached and has reached the alarming level especially when breaching the 95 % confidence bands at the beginning, the latter half and the end of the holdout year 2014. That is, in terms of the river flow in the holdout year 2014, the Kelantan River has experienced more than alarming river flow levels in the beginning and the latter half of the holdout year before the occurrence of the catastrophic flooding at the end of the year 2014. Figure 5 showed that the maximum river flow in December 2014 that caused the catastrophic flood is around 4 times higher than the peak river flow level that occurred at least 5 months earlier. RMSE criterion was used to test the performance of the ARIMA model and according to [16], a notable number of research studies in the context of Malaysia used it. The performance criterion used for both forecasting models, ARIMA and RQA, was RMSE. However, the RQA model also takes normalized mean square error (NMSE) into consideration in addition to RMSE.
4. Conclusion
The present paper reviewed briefly the river floods forecasting methods currently used worldwide with a specific focus in the context of the Kelantan River in Malaysia. A summary of the forecasting methods such as machine learning, statistical and chaos theory has been provided with a focus on the methods used for the forecasting of Kelantan River. This review paper has also demonstrated the capability of the ARIMA method in the early warning detection. The values that fall outside the confidence bands can be considered as an early warning as indicated by the dangerous aberrant volumes of the river flow. These bands can be incorporated into an early warning system as potential predictors of an oncoming extreme event so that populated areas surrounding Kelantan River can take precautionary measures as soon as they are breached. The recurrence plot and recurrence quantification analysis is a novel and useful method especially for the analysis of the river flooding time series data. The authors have also used this technique for flood forecasting; however, its further rigorous and thorough work in this direction can be carried out in the future. This paper suggests the exploration of recurrence analysis method as a future direction for research and development in combination with other appropriate methods such as ARIMA and machine learning methods for dealing with the recurrent rivers flooding in Malaysia. Our future work will also focus on the probabilistic methods of forecasting river flow. A reasonably acceptable prediction of river streamflow is significantly important in disaster management and water resources management.

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