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Macroeconomic Implications of Virtual Water Imports in Iran: A Vector Autoregression Analysis, 2003–2022

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Abstract

Water scarcity is a critical challenge for the global economy in the 21st century, particularly in arid and semi-arid countries such as Iran. Virtual water imports – the water embedded in imported goods – have emerged as an important mechanism to alleviate domestic water shortages. However, the macroeconomic implications of VWI remain underexplored, especially in resource-constrained economies. This study addresses this gap by analyzing the impact of VWI on key macroeconomic indicators in Iran over the period 2003–2022, including trade balance, GDP growth, government revenue, government expenditure, and foreign exchange reserves. To capture the dynamic interrelationships among these variables, a VAR model is employed.The empirical strategy integrates both financial cost and opportunity cost perspectives to provide a comprehensive assessment of how VWI shocks propagate through the macroeconomic system. Standard time-series procedures, including unit root tests and information-criterion – based lag selection, are applied, followed by impulse response functions and forecast error variance decomposition to analyze the short – and long-run effects of VWI shocks. The estimation results indicate that VWI exerts a significant negative impact on Iran's trade balance, with a first-lag coefficient of −0.18, and reduces foreign exchange reserves by 0.09% in the first period and an additional 0.04% in the second period. GDP growth is adversely affected, with a reduction of −0.11 in the first lag, reflecting resource misallocation and diminished economic efficiency. In contrast, VWI contributes positively to government revenue in the short run, with a first-lag coefficient of +0.13, highlighting short-term fiscal benefits. The variance decomposition results further show that VWI shocks account for approximately 47% of the long-run fluctuations in the trade balance and 36% of the variability in economic growth. The findings highlight the dual nature of VWI: while they help mitigate immediate water scarcity, they simultaneously impose significant long-term economic and external-sector trade-offs. For Iran and similar water-scarce economies, these results underscore the need to reduce structural dependence on VWI through investment in water-efficient technologies, enhancement of agricultural productivity, and broader economic diversification. Aligning such strategies with the Sustainable Development Goals can strengthen macroeconomic resilience, preserve foreign exchange reserves, and support sustainable long-term growth.

Keywords:
Virtual Water Imports, Macroeconomic Impacts, Trade Balance, Resource-Scarce Economies.

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1. Introduction

Water scarcity has become one of the most pressing challenges facing the global economy in the 21st century. As water resources are increasingly depleted, many countries rely on virtual water imports[1]– the water embedded in the production of imported goods – to alleviate domestic water shortages and sustain economic activities. Iran, located in one of the most arid regions of the world, has faced persistent water stress, making the role of VWI critical for its economic stability and food security. However, the implications of these imports extend beyond water management, influencing key macroeconomic variables such as the trade balance[2], government expenditure[3], and foreign reserves.

1.1. Problem statement

In Iran, persistent water scarcity has led policymakers to rely heavily on VWI to secure food supplies and stabilize domestic production. While this strategy temporarily alleviates physical water constraints, it simultaneously requires substantial allocations of scarce foreign exchange and may alter key macroeconomic indicators such as the trade balance, economic growth, government revenue[4], and foreign reserves. However, despite the growing dependence on VWI, there is limited empirical evidence on whether this reliance supports or undermines Iran's macroeconomic stability in the medium and long run. The core problem addressed in this study is the lack of a comprehensive, quantitative assessment of how VWI affect Iran's macroeconomic performance and the opportunity costs that arise when foreign exchange resources are diverted toward importing water-intensive goods instead of financing domestic productive investments.

Despite the breadth of studies in the field of virtual water trade[5], a significant research gap remains in the existing literature. Previous research has primarily focused on two areas:
(1) quantifying the physical flows of virtual water and identifying global trade patterns, and (2) examining the environmental consequences of this trade for water resource sustainability.

However, a comprehensive and quantitative analysis of the macroeconomic effects of VWI, particularly in resource-constrained economies such as Iran, has been overlooked. In particular, the consequences of VWI for key variables such as trade balance, gross domestic product[6] growth, and foreign reserves in Iran remain inadequately addressed.

This study examines how VWI impact Iran's macroeconomic dynamics, particularly over the period from 2003 to 2022, a time marked by economic fluctuations and increasing pressures on water and financial resources.

Accordingly, this study is guided by the following main research question:
Does reliance on VWI support or hinder Iran's macroeconomic stability?
To operationalize this overarching question, the study addresses three specific research questions:

1. What is the impact of VWI on Iran's trade balance, economic growth, and foreign exchange reserves?
2. How do the short-term financial benefits of VWI, such as increased government revenue, compare with its long-term costs, particularly regarding foreign exchange reserves?
3. What is the opportunity cost of allocating foreign exchange to VWI instead of investing in domestic productive sectors?

In line with these questions, the objectives of this study are threefold: (1) to analyze the impact of VWI on key macroeconomic variables, (2) to evaluate the financial trade-offs of VWI, and (3) to estimate the opportunity costs of allocating foreign exchange resources to VWI instead of domestic productive sectors.

Research hypotheses

H1: VWI have a statistically significant effect on Iran's trade balance, economic growth, and foreign exchange reserves.
H2: The long-term costs of VWI, particularly in terms of foreign exchange depletion, outweigh its short-term financial benefits.
H3: Allocating foreign exchange resources to VWI entails a positive and economically meaningful opportunity cost relative to investing in domestic productive sectors.

This study seeks to answer whether VWI, beyond providing food security and compensating for water shortages, have become a deterrent to macroeconomic stability in Iran. More precisely, the main question is: what opportunity costs does allocating limited foreign exchange resources to VWI impose on the Iranian economy, and how does its dynamic interaction with macroeconomic variables affect long-term economic stability? Focusing on the period 2002–2023, this study addresses the following main questions:

1) What is the impact of VWI on Iran's trade balance, economic growth, and foreign exchange reserves?

2) How do the short-term financial benefits of VWI, such as increased government revenue, compare to its long-term costs, particularly regarding foreign exchange reserves?

[1] Virtual Water Imports (VWI)
[2] Trade Balance (TB)
[3] Government Expenditure (GE)
[4] Government Revenue (GR)
[5] Virtual Water Trade (VWT)
[6] Gross Domestic Product (GDP)

3) What is the opportunity cost of allocating foreign exchange to VWI instead of investing in domestic productive sectors?

Several recent studies have advanced our understanding of VWT, but they do so along relatively narrow and largely disconnected lines. A first strand of work focuses on tracking physical flows and trade patterns. For example, Boudhar et al., (2023) and Shehata et al., (2023) document that Morocco and Egypt, respectively, are net importers of virtual water, while Zhong et al., (2023) show that, at the global level international trade alleviates water scarcity for about 2.2 billion people in high-income countries but worsens it for approximately 2.1 billion people in low-income countries. Although these studies provide valuable evidence on the distributional and hydrological consequences of VWT, their scope remains largely biophysical: they do not examine how these trade patterns feed back into macroeconomic aggregates such as growth, trade balance, or foreign exchange reserves.

A second strand of the literature examines the sustainability and vulnerability implications of VWT. Hekmatnia et al., (2023) propose a policy framework and find no positive correlation between the water abundance of exporting countries and global freshwater sustainability, while Du et al., (2022) report an 18.9% increase in the vulnerability of global VWT between 2005 and 2015 and develop a framework to measure the gap between actual and ideal virtual water transfers. Complementing these global analyses, Hekmatnia et al., (2024) introduce a novel classification system for VWT designed to support the sustainability of global freshwater resources, and Hekmatnia et al., (2022) develop a policy framework that similarly concludes there is no positive correlation between exporter-country water abundance and global freshwater sustainability. Collectively, these contributions move beyond simple flow accounting and highlight the risks and governance challenges associated with VWT; however, they are still predominantly concerned with environmental sustainability indices and qualitative policy guidance.

What is largely missing in both strands is a systematic and dynamic macroeconomic perspective. The existing studies rarely quantify how reliance on VWI interacts with macroeconomic performance, for example through its effects on the trade balance, economic growth, government revenue, or foreign exchange reserves, nor do they explicitly consider the opportunity costs of allocating scarce foreign exchange to VWT rather than to domestic productive investment. In other words, current VWT research tends to treat economic variables either as exogenous drivers or as contextual background, rather than as core outcomes to be modelled. The present study addresses this gap by using a VAR framework and complementary financial and opportunity-cost analyses to examine the macroeconomic consequences of VWI for Iran over the period 2003-2022.

Although the concept of virtual water has been widely examined in the context of environmental sustainability and water resource management, its macroeconomic implications remain under-researched. Most existing studies focus on the environmental benefits or production-side analysis of VWI, often neglecting their impact on key economic indicators such as trade balance, GDP growth, and foreign reserves. Additionally, the literature on how the financial and opportunity costs associated with VWI affecet resource allocation in resource-constrained economies-such as Iran- is limited. This article addresses this gap by integrating econometric modelling with financial and opportunity cost analyses to provide a comprehensive evaluation of VWI's macroeconomic impacts (Deng et al., 2021).

This research is novel in its approach, employing a Vector Autoregression[1] model to quantify the dynamic relationships between VWI and macroeconomic indicators in Iran from 2003 to 2022. The study also introduces a financial cost model to compare the costs of importing virtual water with domestic production, as well as an opportunity cost framework to assess productivity lost due to foreign exchange allocations to VWI. The objectives are threefold: (1) to analyze the impact of VWI on key economic variables, (2) to evaluate the financial trade-offs of VWI, and (3) to estimate the opportunity costs of allocating resources to VWI instead of other productive sectors. These insights aim to guide policymakers in making informed decisions about water management and economic resource allocation.

Tahami Pourzarandi and Abedi (2017) found that the industrial sector in Zanjan Province is a net exporter of virtual water. Piri et al., (2025) show that exchange rate fluctuations and economic growth have a significant and positive impact on VWT.

Overall, the recent literature on VWT has advanced our understanding of flow patterns, distributional impacts, and sustainability concerns. However, these contributions remain largely disconnected from the macroeconomic domain. Studies in the first strand map the physical movements of virtual water and identify net-importing or net-exporting countries, while those in the second strand focus on vulnerability assessments and sustainability frameworks. Despite their value, neither group examines how dependence on VWI influences macroeconomic outcomes such as the trade balance, economic growth, government revenue, or foreign exchange reserves. Moreover, the existing work does not quantify the opportunity costs associated with allocating

[1] Vector Autoregression (VAR)

scarce foreign exchange to VWI rather than domestic productive sectors.

These gaps directly motivate the objectives and research questions of the present study, which aim to (1) assess the macroeconomic effects of VWI using a VAR framework, (2) evaluate the financial trade-offs involved, and (3) estimate the opportunity cost of diverting foreign exchange resources toward water-intensive imports. By linking VWI to macroeconomic performance in a dynamic, model-based setting, this study extends the literature into an area that has remained underexplored.

The remainder of this article is structured as follows. Section 2 details the research methodology, including the VAR model specification, cost analysis frameworks, and data sources. Section 3 presents the findings, beginning with stationarity tests and lag selection, followed by an in-depth analysis of the VAR model results, impulse response functions[1], and variance decomposition. Section 4 discusses the financial and opportunity costs of VWI, focusing on trends over the 2003–2022 period. Section 5 examines the robustness of the results using alternative specifications and stability tests. Finally, Section 6 concludes the study by summarizing key insights, policy implications, and directions for future research.

2. Method

2.1. Research design

This study adopts a quantitative and empirical research design based on time series econometric analysis. The purpose of the study is to examine the macroeconomic effects of VWI on key economic indicators in Iran. The analysis focuses on the dynamic relationships between VWI and several macroeconomic variables, including economic growth, the trade balance, government revenue, and foreign exchange reserves over the period 2003-2022.

Given the interdependent nature of macroeconomic variables, the study employs a VAR framework. The VAR model is particularly suitable for this research because it treats all variables as endogenous and allows for the examination of dynamic interactions among them. Unlike single equation models, VAR models capture the feedback effects between variables and provide a flexible structure for analyzing how shocks to one variable propagate through the entire economic system over time.

In addition to estimating the dynamic relationships among the variables, the study also evaluates the financial implications and opportunity costs associated with VWI. In particular, it investigates how the allocation of foreign exchange resources toward water intensive imports may influence broader macroeconomic performance.

2.2. Model specification

To analyze the dynamic interactions between VWI and macroeconomic indicators, a standard VAR model is employed. In its general form, the VAR(p) model can be written as

$$Y_t = A_1 Y_{t-1} + A_2 Y_{t-2} + \cdots + A_p Y_{t-p} + \varepsilon_t \quad (1)$$

Where,

- Y_t is a vector of endogenous variables
- A_i represents matrices of coefficients
- p denotes the optimal lag length
- ε_t is a vector of error terms

In this study, the vector of endogenous variables includes:

- Virtual Water Imports (VWI)
- Economic Growth or GDP Growth
- Trade Balance (TB)
- Government Revenue (GR)
- Foreign Exchange Reserves (R)

All variables are included simultaneously in the VAR system to capture the mutual interactions among them. This framework allows the study to investigate how shocks to VWI affect macroeconomic indicators and how macroeconomic conditions may, in turn, influence VWI.

Before estimating the VAR model, it is necessary to examine the stationarity properties of the time-series data to avoid spurious regression results. Stationarity implies that the statistical properties of a variable, such as its mean and variance, remain constant over time.

To test for stationarity, standard unit root tests are applied, including the Augmented Dickey–Fuller[2] test. The null hypothesis of the ADF test is that the series contains a unit root (non-stationary), while the alternative hypothesis suggests that the series is stationary.

If any variable is found to be non-stationary in levels, the test is repeated after taking first differences. Only stationary variables are used in the VAR estimation to ensure the validity and reliability of the econometric results.

An important step in VAR estimation is determining the optimal lag length (p). Choosing too few lags may lead to model misspecification and omitted dynamic relationships, while too many lags may reduce estimation efficiency and consume degrees of freedom.

The optimal lag length is determined using several commonly used information criteria, including:

[1] Impulse Response Functions (IRFs)

[2] Augmented Dickey–Fuller (ADF)

- Akaike Information Criterion (AIC) Schwarz Bayesian Criterion (SIC/BIC)
- Hannan–Quinn Criterion (HQ)

The lag order that minimizes these criteria is selected as the optimal specification for the VAR model.

To explore the dynamic effects of shocks in the VAR system, Impulse Response Functions (IRFs) are estimated. Impulse response analysis traces the effect of a one-time shock to one variable on the current and future values of all variables in the system.

In the context of this study, impulse response functions are used to examine how a shock to VWI affects macroeconomic variables such as economic growth, the trade balance, government revenue, and foreign exchange reserves over time. This approach provides valuable insights into the dynamic transmission mechanisms through which VWI influences macroeconomic performance.

To further understand the relative importance of shocks within the system, Forecast Error Variance Decomposition[1] is conducted. Variance decomposition measures the proportion of the forecast error variance of each variable that can be attributed to shocks in each variable within the VAR system.

This analysis helps identify the extent to which fluctuations in macroeconomic indicators are explained by shocks to VWI compared to shocks originating from other macroeconomic variables. Therefore, forecast error variance decomposition provides additional evidence regarding the macroeconomic significance of VWI in the Iranian economy. Together, the VAR estimation, impulse response analysis, and variance decomposition provide a comprehensive framework for examining the dynamic and macroeconomic implications of VWI.

- A VAR model was developed to estimate the macroeconomic impact of VWT in Iran from 2003 to 2022. This model was based on the studies by Hirwa et al., (2023) for the equations 2 to 5 and Fracasso (2014) for the equation 6. The VAR model includes the following equations:

[1] Forecast Error Variance Decomposition (FEVD)

$$TB_t = \alpha_{10} + \sum_{i=1}^{p} \alpha_{1i} TB_{t-i} + \sum_{j=1}^{q} \beta_{1j} GR_{t-j} + \sum_{k=1}^{r} \gamma_{1k} GE_{t-k} + \sum_{l=1}^{s} \delta_{1l} GDP_{t-l} + \sum_{m=1}^{u} \theta_{1m} R_{t-m} + \mu_{11} VWI_t + \mu_{12} P_t + \mu_{13} Y_t + \varepsilon_{1t} \quad (2)$$

$$GR_t = \alpha_{20} + \sum_{i=1}^{p} \alpha_{2i} TB_{t-i} + \sum_{j=1}^{q} \beta_{2j} GR_{t-j} + \sum_{k=1}^{r} \gamma_{2k} GE_{t-k} + \sum_{l=1}^{s} \delta_{2l} GDP_{t-l} + \sum_{m=1}^{u} \theta_{2m} R_{t-m} + \mu_{21} VWI_t + \mu_{22} P_t + \mu_{23} Y_t + \varepsilon_{2t} \quad (3)$$

$$GE_t = \alpha_{30} + \sum_{i=1}^{p} \alpha_{3i} TB_{t-i} + \sum_{j=1}^{q} \beta_{3j} GR_{t-j} + \sum_{k=1}^{r} \gamma_{3k} GE_{t-k} + \sum_{l=1}^{s} \delta_{3l} GDP_{t-l} + \sum_{m=1}^{u} \theta_{3m} R_{t-m} + \mu_{31} VWI_t + \mu_{32} P_t + \mu_{33} Y_t + \varepsilon_{3t} \quad (4)$$

$$GDP_t = \alpha_{40} + \sum_{i=1}^{p} \alpha_{4i} TB_{t-i} + \sum_{j=1}^{q} \beta_{4j} GR_{t-j} + \sum_{k=1}^{r} \gamma_{4k} GE_{t-k} + \sum_{l=1}^{s} \delta_{4l} GDP_{t-l} + \sum_{m=1}^{u} \theta_{4m} R_{t-m} + \mu_{41} VWI_t + \mu_{42} P_t + \mu_{43} Y_t + \varepsilon_{4t} \quad (5)$$

$$R_t = \alpha_{50} + \sum_{i=1}^{p} \alpha_{5i} TB_{t-i} + \sum_{j=1}^{q} \beta_{5j} GR_{t-j} + \sum_{k=1}^{r} \gamma_{5k} GE_{t-k} + \sum_{l=1}^{s} \delta_{5l} GDP_{t-l} + \sum_{m=1}^{u} \theta_{5m} R_{t-m} + \mu_{51} VWI_t + \mu_{52} P_t + \mu_{53} Y_t + \varepsilon_{5t} \quad (6)$$

2.3. Model variables

Trade balance is measured as the difference between Iran's total exports and imports of goods and services as a percentage of GDP. Annual data are obtained from the Central Bank of Iran[2].

- Government revenue (GR) includes tax and non-tax revenue as a percentage of GDP, based on financial data from the Central Bank.

- Government expenditure (GE) measures total government consumption and investment expenditure as a percentage of GDP, using financial data.

- The annual growth rate of GDP indicates economic growth, based on the series of Iranian gross domestic product at constant prices from 2003 to 2022, using World Bank data.

- Foreign exchange reserves (R) are Iran's total reserves minus gold as a percentage of GDP, using IMF data.

- VWI are measured as the total volume of selected imported products related to Iran's virtual water flow, compiled from trade data.

[2] Central Bank of Iran (CBI)

Table 1. Characteristics of variables, sources and time period of data

Variable	Symbol	Definition/Unit	Data source	Time frame	Reason for choosing
Trade balance	TB	(Export - Import) / GDP (%)	Central bank of Iran	2003-2022	The main indicator of the health of the external sector of the economy
Government revenue	GR	Tax and non-tax revenues/GDP (%)	Central Bank of Iran	2003-2022	Indicates the financial capacity of the government
Government expenditure	GE	Government Consumption and Capital Expenditure / GDP (%)	Central Bank of Iran	2003-2022	Indicates the direction of fiscal policy
Economic growth	GDP	Annual Growth Rate of Gross Domestic Product (GDP)	World Bank	2003-2022	Main measure of economic performance
Foreign exchange reserves	R	Total Gold Reserves minus GDP (%)	International Monetary Fund	2003-2022	Vulnerability index and shock resilience
Virtual water import	VWI	Volume of virtual water imported through selected goods (million cubic meters)	Trade Data of the Ministry of Agricultural Jihad and Customs	2003-2022	Key research variable
Food price index	P	International Food Price Index (base year 2010=100)	International Monetary Fund	2003-2022	To control the impact of global import inflation
Productivity index	Y	Composite Index of Principal Agricultural Yield (Base Year 2003=100)	FAO	2003-2022	Domestic production capacity control

- The global food price index (P) is the IMF's price index of selected products, adjusted for inflation and exchange rates.
- The crop yield index (Y) represents Iran's domestic agricultural productivity, based on an index of FAO's major crop yields (Table 1).

p, q, r, s, and u represent the optimal intercepts for each variable.

2.4. Validity and reliability

Ensuring the validity and reliability of the empirical analysis is an essential component of quantitative macroeconomic research. In this study, several procedures are implemented to enhance the credibility and robustness of the data and econometric results.

First, data reliability is ensured through the use of official and internationally recognized statistical sources. The macroeconomic variables are obtained from the Central Bank of Iran, the World Bank (World Development Indicators), and the International Monetary Fund[1]. These institutions provide standardized and consistently compiled datasets that are widely used in empirical economic research. The reliance on these sources reduces the risk of measurement errors and enhances the comparability of the time-series data.

Second, measurement validity is addressed through the operational definition of variables in accordance with established economic literature. Variables such as trade balance, government revenue, and government expenditure are expressed as percentages of GDP to ensure comparability across time and to control for scale effects. The VWI variable is constructed based on trade statistics combined with virtual water coefficients derived from previous studies on virtual water flows, which strengthens the conceptual validity of the indicator.

Third, econometric reliability and robustness are evaluated using several standard diagnostic procedures. Prior to estimation, the stationarity of the time-series variables is examined using unit root tests to avoid spurious regression problems. The appropriate lag structure of the VAR model is determined using established information criteria, including the Akaike Information Criterion[2] and the Schwarz Bayesian Criterion (BIC). In addition, post-estimation analyses such as impulse response functions (IRFs) and forecast

[1] International Monetary Fund (IMF)

[2] Akaike Information Criterion (AIC)

error variance decomposition (FEVD) are conducted to assess the dynamic consistency and stability of the estimated relationships.

Finally, data series were checked for consistency, missing observations, and potential structural irregularities before estimation. These procedures collectively enhance the validity, reliability, and transparency of the empirical framework used in this study.

2.5. Data and data collection procedures

This study uses annual macroeconomic and trade data for Iran covering the period 2003-2022. The dataset is constructed to capture the interaction between VWI and key macroeconomic indicators that reflect external balance, fiscal stance, real economic activity, and external liquidity conditions. All series are collected from official and internationally recognized statistical sources to ensure reliability and comparability over time. The variables included in the analysis are:

- Trade Balance, measured as the difference between Iran's total exports and imports of goods and services as a percentage of GDP. Annual data are obtained from the Central Bank of Iran (CBI).
- Government Revenue (GR), defined as total tax and non-tax revenues as a percentage of GDP, based on the fiscal statistics of the Central Bank of Iran.
- Government Expenditure (GE), measuring total government consumption and investment expenditures as a percentage of GDP, is also drawn from CBI fiscal data.
- Economic Growth (GDP), proxied by the annual growth rate of real gross domestic product, using the time series of Iranian GDP at constant prices from 2003 to 2022 collected from the World Bank's World Development Indicators (WDI).
- Foreign Exchange Reserves (R), defined as total international reserves excluding gold, expressed as a percentage of GDP, obtained from the International Monetary Fund (IMF).
- VWI, measured as the total virtual water content embodied in selected imported agricultural and food products that are relevant for Iran's virtual water flows. This variable is constructed by combining annual import quantities and values from Iran's official trade statistics (customs and national trade data) with product-specific virtual water coefficients from the existing literature and international databases on virtual water content.
- Global Food Price Index (P), defined as the IMF food price index for a basket of agricultural and food commodities, adjusted for inflation and exchange rate movements where appropriate.

The data collection procedure involved several steps.

First, the time frame 2003-2022 was selected to ensure a sufficiently long period for time-series analysis while reflecting the availability and consistency of macroeconomic and trade data in Iran.

Second, the macroeconomic series (TB, GR, GE, GDP, R) were downloaded from the Central Bank of Iran, the World Bank (WDI), and the IMF using their publicly available statistical databases.

Third, trade data for the selected agricultural and food products were obtained from Iran's customs and national trade statistics, and then matched with virtual water coefficients to construct the annual VWI series.

Finally, the global food price index was extracted from the IMF commodity price database.

All variables are compiled at annual frequency, which is appropriate for capturing medium-term macroeconomic dynamics and is consistent with the availability of fiscal and external sector data. Where necessary, variables are expressed as percentages of GDP to ensure comparability across time and to mitigate scale effects. Data series were checked for internal consistency, missing values, and structural breaks. When minor inconsistencies or missing observations were detected, they were addressed using standard interpolation and cross-checking across different data sources.

Table 1 summarizes the definitions, measurement units, data sources, and time period for each variable included in the analysis. Overall, the reliance on official national and international datasets and the transparent construction of the VWI indicator support the methodological rigor and reproducibility of the empirical analysis.

2.6. Data analysis procedure

The empirical analysis in this study follows a systematic multi-step procedure in order to ensure transparency and replicability of the results.

First, the time-series properties of all variables are examined using unit root tests to determine whether the variables are stationary or contain stochastic trends. Testing for stationarity is necessary to avoid spurious regression results that may arise when non-stationary variables are used in time-series models.

Second, once the integration properties of the variables are identified, the appropriate lag length for the VAR model is determined. The optimal lag structure is selected using standard information criteria, including the Akaike Information Criterion (AIC) and the Schwarz Bayesian Criterion (BIC). Selecting the optimal lag length is essential to capture the dynamic relationships among the variables while avoiding model over-parameterization.

Third, the VAR model is estimated using the selected lag structure. The VAR framework allows each variable in the system to be treated as endogenous and modeled as a function of its own past values and the lagged values of all other variables in the system.

Fourth, the dynamic interactions among variables are analyzed using Impulse Response Functions. These functions trace the time path of the response of one variable to a one-time shock in another variable while holding other shocks constant. This approach allows the study to examine how shocks to VWI affect macroeconomic variables such as trade balance, government revenue, and economic growth over time.

Fifth, Forecast Error Variance Decomposition is conducted to evaluate the relative contribution of each structural shock to the variability of the endogenous variables. This analysis helps determine the extent to which fluctuations in macroeconomic variables can be explained by shocks in VWI and other variables in the system.

All econometric estimations and statistical analyses are conducted using standard econometric software packages commonly employed in time-series research. The overall analytical framework ensures that the results are transparent, methodologically rigorous, and replicable by other researchers.

3. Result

This section presents the empirical findings obtained from the econometric analysis. The results are reported in a descriptive and objective manner, focusing on the statistical outcomes of the estimation procedures. The interpretation of these findings and their theoretical and policy implications are discussed separately in the subsequent discussion section.

The analysis proceeds in several steps. First, the stationarity properties of the variables are examined using unit root tests. Second, the optimal lag length for the VAR model is determined based on standard information criteria. Third, the VAR model is estimated to capture the dynamic relationships among the variables. Finally, impulse response functions and forecast error variance decomposition are used to analyze the dynamic effects of shocks within the system.

3.1. Stationarity tests and lag selection

The stationarity analysis of the time series data revealed varying degrees of integration among the variables examined. The Augmented Dickey-Fuller test results indicate that Trade Balance (TB), GDP Growth, and Food Price Index (P)-were stationary at levels, with test statistics of -3.12, -4.25, and -3.08 respectively, all exceeding the critical value of -2.93 at the 5% significance level. These variables demonstrated mean-reverting properties and could be included in the VAR model without transformation. However, most variables exhibited non-stationary behaviour at levels, necessitating first-difference transformation to achieve stationarity. Government Revenue (GR), Government Expenditure (GE), Reserves (R), VWI, and Crop Yield Index (Y) all became stationary after first differencing, as shown by their transformed Augmented Dickey-Fuller (ADF) statistics ranging from -3.54 to -5.02, well beyond the critical value threshold. The p-values for these differenced series were all below 0.01, strongly rejecting the null hypothesis of non-stationarity. The lag selection process, guided by the Akaike Information Criterion (AIC), suggested an optimal lag length of two periods for the VAR model. This selection balances the trade-off between model parsimony and adequate capture of dynamic relationships.

The chosen lag structure provides sufficient temporal depth to capture the delayed effects of policy changes and economic shocks, while maintaining model efficiency and avoiding over-parameterization. These findings have important implications for model specification. The presence of both I(0) and I(1) variables indicates the need for a careful approach to cointegration analysis and the potential use of a Vector Error Correction Model[1] if long-run relationships are identified. The mixed order of integration also underscores the complexity of the relationships between VWI and macroeconomic variables in the context of Iran (Table 2).

3.2. Lag length selection

Determining the optimal lag length is crucial for specifying the VAR model, as it directly affects the model's ability to capture dynamic relationships while maintaining parsimony. This analysis employed three widely accepted information criteria – the Akaike Information Criterion (AIC), Schwarz Criterion (SC), and Hannan–Quinn Criterion (HQ) – to identify the most appropriate lag structure for the model. The results indicate that a lag length of two periods provides the optimal specification across all three criteria. Specifically, the Akaike Information Criterion (AIC) reached its minimum value of -8.45 at lag 2, compared to -8.12 at lag 1 and -8.23 at lag 3. Both the SC and HQ criteria corroborate this finding, showing their lowest values of -7.68 and -8.12, respectively, at the second lag. The consistency across all three information criteria provides robust support for selecting a two-period lag structure. The choice of two lags is also theoretically justified, given the nature of macroeconomic relationships and policy transmission mechanisms in Iran's economy. This lag structure allows sufficient time for the effects of VWI and other macroeconomic variables to manifest, while avoiding the potential over-parameterization that might occur with longer lag specifications (Table 3).

[1] Vector Error Correction Model (VECM)

Table 2. Unit root test

Variable	Level ADF statistic	1st Diff. ADF statistic	Critical value (5%)	p-value	Stationarity	Transformation
TB	-3.12	-	-2.93	0.042	Stationary	None
GR	-2.45	-4.87	-2.93	0.000	Non-stationary	First differencing
GE	-1.98	-3.65	-2.93	0.007	Non-stationary	First differencing
GDP	-4.25	-	-2.93	0.001	Stationary	None
R	-2.12	-3.54	-2.93	0.010	Non-stationary	First differencing
VWI	-2.67	-5.02	-2.93	0.000	Non-stationary	First differencing
P	-3.08	-	-2.93	0.045	Stationary	None
Y	-1.88	-4.12	-2.93	0.001	Non-stationary	First differencing

Table 3. Determination of optimal lag length

Lag length	AIC	SC	HQ
1	-8.12	-7.45	-7.89
2	-8.45	-7.68	-8.12
3	-8.23	-7.32	-7.89

Furthermore, the chosen lag length appropriately balances capturing dynamic interactions with preserving degrees of freedom, which is particularly important given the annual frequency of the data and the sample size constraints. This optimal lag specification will be used in the subsequent VAR analysis, providing a foundation for investigating the dynamic relationships between VWI and key macroeconomic variables. The two-period lag structure will be especially valuable for examining both the immediate and delayed effects of policy changes and economic shocks within Iran's macroeconomic framework.

3.3. Results of the VAR model

3.3.1. Trade balance

The estimation results for the Trade Balance equation reveal significant dynamic relationships between VWI and Iran's trade position, with several key variables showing statistically significant effects across both lag periods. Notably, the lagged values of the Trade Balance itself indicate strong persistence, with a first-lag coefficient of 0.48 ($p < 0.001$) and a second-lag coefficient of 0.15, demonstrating substantial inertia in Iran's trade position over time.

VWI display a particularly strong and negative relationship with the trade balance, as shown by coefficients of -0.18 and -0.08 for the first and second lags, respectively. The high statistical significance ($p < 0.000$) of these coefficients indicates that increases in VWI consistently lead to a deterioration in Iran's trade balance, with the effect most pronounced in the period immediately following the import increase. This finding is consistent with theoretical expectations, as VWI represent a direct outflow of foreign exchange.

Government Revenue (GR) and GDP are positively associated with the trade balance, with first-lag coefficients of 0.16 ($p = 0.025$) and 0.09 ($p = 0.041$), respectively. These relationships suggest that improved fiscal conditions and economic growth tend to strengthen Iran's trade position, although the effects diminish substantially in the second lag.

Conversely, Government Expenditure (GE) shows a negative relationship (-0.12 in the first lag), although with marginal statistical significance ($p = 0.054$). The role of foreign exchange reserves (R) is significant and negative (-0.10 in the first lag, $p = 0.010$), potentially indicating that higher reserves may lead to more liberal import policies. While the Food Price Index (P) and Crop Yield Index (Y) have positive coefficients (0.04 and 0.05, respectively, in the first lag), their effects are not statistically significant at conventional levels ($p > 0.05$), suggesting that domestic agricultural productivity and global food prices may have less direct influence on Iran's trade balance than other macroeconomic factors (Table 4).

Table 4. Estimated coefficients for the trade balance (TB) equation

Variable	Lag 1 coefficient	Lag 2 coefficient	Standard error	p-value
TB_{t-1}	0.48	0.15	0.07	0.001
GR_{t-1}	0.16	-0.02	0.06	0.025
GE_{t-1}	-0.12	-0.04	0.05	0.054
GDP_{t-1}	0.09	0.03	0.04	0.041
R_{t-1}	-0.10	-0.05	0.03	0.010
VWI_{t-1}	-0.18	-0.08	0.02	0.000
P_{t-1}	0.04	0.02	0.03	0.112
Y_{t-1}	0.05	0.01	0.02	0.075

These findings provide important insights into the complex relationships between VWI and Iran's external sector performance, highlighting the significant role of VWT in shaping the country's overall trade position. The results underscore the need for careful consideration of virtual water import policies within the broader context of macroeconomic management and trade policy.

3.3.2. Government revenue

The estimation results for the Government Revenue equation reveal strong persistence in revenue dynamics, with the first-lag coefficient of GR at 0.67 ($p < 0.000$) and the second-lag coefficient at 0.31. This pronounced autoregressive pattern suggests that Iran's government revenue displays considerable inertia, reflecting the structural characteristics of the country's revenue-generating mechanisms and the relatively stable nature of its main revenue sources.

VWI show a significant positive relationship with government revenue, with coefficients of 0.13 and 0.06 for the first and second lags, respectively ($p = 0.001$). This positive association may be due to customs duties and other trade-related revenues generated from VWI, indicating that, despite their impact on the trade balance, these imports contribute positively to government fiscal resources. This finding underscores the complex trade-offs involved in virtual water import policies.

The Trade Balance exhibits a modest but statistically significant positive relationship with government revenue (first-lag coefficient of 0.12, $p = 0.043$), indicating that improvements in the trade position tend to enhance government revenue collection. GDP growth also exhibits a positive association (0.11 in the first lag), though with marginal statistical significance ($p = 0.056$), suggesting that economic growth generally supports revenue generation, albeit with some uncertainty in the relationship.

Government Expenditure (GE) displays a weak positive relationship in the first lag (0.08) but becomes slightly negative in the second lag (-0.02), with marginal statistical significance ($p = 0.085$). This pattern may reflect the complex dynamics between spending and revenue generation in Iran's fiscal system. Notably, foreign exchange reserves (R) exhibit a weak negative association that is not statistically significant ($p = 0.133$), indicating that reserve levels may not be a crucial determinant of government revenue performance.

The Food Price Index (P) and Crop Yield Index (Y) both display relatively modest coefficients (0.07 and 0.03, respectively, in the first lag) with marginal statistical significance ($p > 0.05$), indicating that although agricultural factors may influence government revenue, their impact is less pronounced than that of other macroeconomic variables. This suggests that Iran's government revenue structure may not be highly sensitive to agricultural sector performance or global food price fluctuations (Table 5).

Table 5. Estimated coefficients for the government revenue (GR) equation

Variable	Lag 1 coefficient	Lag 2 coefficient	Standard error	p-value
TB_{t-1}	0.12	0.04	0.05	0.043
GR_{t-1}	0.67	0.31	0.08	0.000
GE_{t-1}	0.08	-0.02	0.05	0.085
GDP_{t-1}	0.11	0.02	0.04	0.056
R_{t-1}	-0.05	-0.01	0.02	0.133
VWI_{t-1}	0.13	0.06	0.02	0.001
P_{t-1}	0.07	0.02	0.03	0.091
Y_{t-1}	0.03	-0.01	0.02	0.082

3.3.3. Government expenditure

The estimation results for the Government Expenditure equation reveal strong persistence in spending patterns, with the first-lag coefficient of GE at 0.72 ($p < 0.000$) and the second-lag coefficient at 0.34. This pronounced autoregressive behavior suggests that Iran's government expenditure exhibits significant inertia, reflecting the structural nature of public spending commitments and the institutional framework governing fiscal policy implementation.

Foreign exchange reserves (R) show a significant negative relationship with government expenditure, with coefficients of -0.08 and -0.03 for the first and second lags, respectively ($p = 0.045$). This inverse relationship may indicate a countercyclical pattern, where lower reserves lead to increased government spending, possibly as a policy response to economic challenges. The statistical significance of this relationship underscores the importance of reserve levels in shaping fiscal policy decisions.

Government revenue shows a positive but only marginally significant relationship with expenditure (first-lag coefficient 0.14, $p = 0.073$), suggesting that revenue availability influences spending decisions, though not as strongly as might be expected. Similarly, GDP growth exhibits a modest positive association (first-lag coefficient 0.06, $p = 0.067$), indicating that economic growth tends to support increased government spending, although the relationship is not strongly significant at conventional levels.

Notably, VWI exhibit relatively weak and statistically insignificant effects on government expenditure (coefficients of 0.02 and 0.01, $p = 0.145$). This suggests that virtual water import decisions may not substantially influence government spending patterns, possibly indicating that such imports are mainly driven by private sector activity rather than direct government intervention. The Trade Balance also shows a weak

positive relationship (0.07 in the first lag) with marginal statistical significance ($p = 0.093$).

The Food Price Index (P) and Crop Yield Index (Y) display modest coefficients (0.05 and 0.04, respectively in the first lag) with marginal statistical significance ($p > 0.05$). These results indicate that, while agricultural conditions and global food prices may influence government expenditure decisions, their impact is not as pronounced as that of other macroeconomic factors. This pattern may reflect the government's ability to maintain relatively stable spending despite fluctuations in agricultural sector performance (Table 6).

Table 6. Estimated coefficients for the government expenditure (GE) equation

Variable	Lag 1 coefficient	Lag 2 coefficient	Standard error	p-value
TB_{t-1}	0.07	0.02	0.03	0.093
GR_{t-1}	0.14	0.03	0.04	0.073
GE_{t-1}	0.72	0.34	0.07	0.000
GDP_{t-1}	0.06	0.01	0.03	0.067
R_{t-1}	-0.08	-0.03	0.03	0.045
VWI_{t-1}	0.02	0.01	0.01	0.145
P_{t-1}	0.05	0.02	0.02	0.088
Y_{t-1}	0.04	-0.01	0.01	0.094

3.3.4. GDP growth

The estimation results for the GDP growth equation reveal significant persistence in economic growth dynamics, with a strong first-lag coefficient of 0.55 ($p < 0.000$) and a second-lag coefficient of 0.20. This substantial autoregressive pattern indicates considerable momentum in Iran's economic growth trajectory, suggesting that growth outcomes are strongly influenced by performance in previous periods. The high statistical significance of these coefficients underscores the importance of historical growth patterns in determining current economic performance.

VWI show a significant negative relationship with GDP growth, with coefficients of -0.11 and -0.05 for the first and second lags, respectively ($p = 0.008$). This inverse relationship suggests that increased reliance on VWI may have a detrimental effect on economic growth, possibly through their impact on domestic production capacity and foreign exchange utilization. The statistical significance of this relationship highlights the potential economic costs associated with dependency on VWI.

Trade balance and government revenue (GR) both exhibit positive and statistically significant relationships with GDP growth, with first-lag coefficients of 0.10 ($p = 0.032$) and 0.15 ($p = 0.047$), respectively. These findings suggest that improvements in external trade position and stronger government fiscal performance tend to support economic growth. The positive association between government revenue and growth may reflect the important role of fiscal resources in supporting economic development.

Government expenditure (GE) shows a positive but only marginally significant relationship with growth (0.09 in the first lag, $p = 0.061$), while foreign exchange reserves (R) display a weak negative association (-0.06 in the first lag, $p = 0.067$). These results suggest that government spending may support growth to some extent, but the relationship between reserves and economic performance is more complex and potentially influenced by other macroeconomic factors.

The Crop Yield Index (Y) and Food Price Index (P) have relatively modest coefficients (0.02 and 0.03 respectively in the first lag) with marginal statistical significance. This pattern suggests that, although agricultural productivity and global food prices may influence economic growth, their direct impact is relatively limited compared to other macroeconomic variables. The results indicate that Iran's economic growth is more strongly driven by broader macroeconomic factors than by agricultural sector performance or international food price dynamics (Table 7).

Table 7. Estimated coefficients for the GDPG equation

Variable	Lag 1 coefficient	Lag 2 coefficient	Standard error	p-value
TB_{t-1}	0.10	0.03	0.04	0.032
GR_{t-1}	0.15	0.04	0.03	0.047
GE_{t-1}	0.09	0.02	0.03	0.061
GDP_{t-1}	0.55	0.20	0.07	0.000
R_{t-1}	-0.06	-0.02	0.02	0.067
VWI_{t-1}	-0.11	-0.05	0.02	0.008
P_{t-1}	0.03	0.01	0.01	0.075
Y_{t-1}	0.02	0.01	0.01	0.054

3.3.5. Reserves

Relationship Between VWI and Reserves:

The relationship between VWI and reserves, as indicated by the negative coefficients (-0.09 and -0.04), highlights a critical but often overlooked factor in reserve dynamics. The data suggest that a 1% increase in VWI results in a 0.09% reduction in reserves in the first period, followed by a further 0.04% decline in the subsequent period. This cumulative effect of -0.13% over two periods underscore the significant and persistent impact of VWI on foreign exchange reserves. The strong statistical significance ($p = 0.015$) confirms the robustness of this relationship, ruling out the possibility that it is random or incidental.

This negative relationship can be understood in the context of the economic and environmental costs associated with VWI. Virtual water – embedded in imported goods such as agricultural products – represents a reliance on external water resources to meet domestic demand. While this may alleviate immediate water scarcity, it likely places a strain on foreign exchange reserves due to the financial outflows required to fund these imports. Over time, this dependency on external resources may undermine economic self-sufficiency and erode the country's external buffer, leaving it more vulnerable to external shocks and fluctuations in global commodity prices.

The sequential decline in reserves over two periods (-0.09% in the first and -0.04% in the second) indicates that the impact of VWI is both immediate and persistent, potentially reflecting downstream effects such as reduced agricultural productivity or increased reliance on further imports. This temporal aspect highlights the long-term risks of excessive virtual water dependency, as the cumulative effect on reserves compounds, gradually undermining the country's economic resilience. Furthermore, the fact that the second-period impact, though smaller, remains statistically significant, underscoring the persistence of this relationship.

For Iran, this finding has important policy implications. As a country facing significant water scarcity, Iran's reliance on VWI to supplement domestic water supplies must be carefully managed to avoid excessive pressure on reserves. Policymakers should consider strategies to reduce dependency on VWI, such as investing in water-efficient technologies, promoting domestic agricultural productivity, or diversifying import sources to mitigate foreign exchange outflows. Additionally, the strong link between VWI and reserve depletion suggests that import policy should be integrated into broader reserve management strategies to ensure that short-term solutions to resource constraints do not compromise long-term economic stability.

A. Growth-reserves dynamics

The positive relationship between GDP growth and reserves (0.18 in the first lag, $p = 0.034$) reveals an important economic mechanism. The coefficient indicates that a 1% increase in GDP growth leads to a 0.18% increase in reserves in the subsequent period. This relationship appears to operate through several channels: 1) enhanced export capacity resulting from stronger economic growth; 2) increased foreign investment inflows during periods of growth; 3) greater capacity to accumulate reserves during economic expansion. The second-lag coefficient of 0.05 shows that these positive effects persist, though with diminishing impact.

B. Persistence in reserve accumulation

The strong autoregressive coefficients (0.72 and 0.28) warrant special attention as they reveal important institutional features: 1) the high first-lag coefficient (0.72) suggests that reserve management follows a highly structured policy framework; 2) the combined effect of both lags (1.00) indicates that shocks to reserves tend to have permanent effects; 3) this persistence suggests that policy changes affecting reserves may have long-lasting implications for Iran's external position.

C. Policy interaction effects

The analysis of policy interaction effects reveals a nuanced relationship between fiscal, trade, and environmental factors in shaping reserve accumulation. The positive coefficient for government revenue (0.12) indicates that higher revenues are associated with increases in reserves, suggesting a direct link between fiscal capacity and the ability to strengthen reserves. However, this benefit is offset by the negative impact of VWI (-0.09), which implies that reliance on external environmental resources can erode reserve accumulation. This dynamic suggests a potential trade-off between generating fiscal surpluses and addressing sustainability concerns, highlighting the need for integrated policy frameworks that consider both economic and environmental objectives.

In contrast, the relatively weak coefficient for government expenditure (0.11) suggests that fiscal spending has a limited direct influence on reserve accumulation. This finding may indicate that the effectiveness of government expenditure depends on its composition and alignment with broader economic objectives.

For example, expenditures directed towards productive investments or infrastructure may indirectly contribute to reserves by fostering long-term economic growth, while consumption-oriented spending may have a more neutral or even negative effect. Thus, the limited magnitude of the expenditure coefficient underscores the importance of considering the qualitative aspects of fiscal policy, rather than focusing solely on quantitative increases in spending.

The modest positive effect of the trade balance (0.08) complicates the narrative by indicating that trade-related factors, though important, may play a secondary role in determining reserve levels compared to other variables. This suggests that non-trade factors, such as fiscal policies or external shocks, might have a stronger influence on reserve accumulation. Although a positive trade balance contributes to reserve growth, its relatively small coefficient shows that the relationship is not as robust as might be expected. This may reflect the influence of global economic conditions, exchange rate volatility, or structural dependencies within the economy that weaken the direct impact of trade surpluses on reserves (Table 8).

Table 8. Estimated coefficients for the reserves (R) equation

Variable	Lag 1 coefficient	Lag 2 coefficient	Standard error	p-value
TB_{t-1}	0.08	0.02	0.03	0.049
GR_{t-1}	0.12	0.03	0.03	0.039
GE_{t-1}	0.11	0.02	0.03	0.062
GDP_{t-1}	0.18	0.05	0.04	0.034
R_{t-1}	0.72	0.28	0.07	0.000
VWI_{t-1}	-0.09	-0.04	0.02	0.015
P_{t-1}	0.02	0.01	0.01	0.090
Y_{t-1}	0.04	0.01	0.02	0.082

3.4. Significant relationships in the trade balance

3.4.1. Virtual water import impacts

The VAR model identifies VWI as a destabilizing factor for several key macroeconomic variables. The most pronounced negative effect is on the trade balance, with a coefficient of -0.18. This indicates that VWI exert significant pressure on the external sector, likely due to the financial outflows required to fund such imports. Given the already constrained foreign exchange reserves in countries such as Iran, this finding suggests that reliance on VWI contributes to external vulnerability and reduces the economy's ability to maintain a healthy trade position. The negative effect on GDP growth (-0.11) further highlights the broader economic costs of virtual water dependency. By directing resources towards imports rather than domestic production, VWI may crowd out local industries, suppressing growth and reducing economic efficiency.

Interestingly, VWI has a positive impact on government revenue (+0.13), reflecting fiscal benefits from import-related taxes, tariffs, or associated economic activity. However, this short-term revenue increase must be weighed against the long-term costs of reduced growth and external imbalances. The moderate negative effect on reserves (-0.09) is consistent with previous findings, confirming that VWI deplete foreign exchange reserves over time. Overall, these results suggest that while VWI may provide immediate fiscal benefits, it exacerbates external vulnerabilities and undermines sustainable economic growth.

3.4.2. System persistence

The model reveals strong autoregressive effects across all major variables, highlighting the persistent nature of macroeconomic systems. Reserves have the highest persistence coefficient (+0.72), reflecting stable and structured reserve management practices. This indicates that reserve levels are heavily influenced by their past values, so shocks to reserves – such as those caused by VWI – can have long-lasting effects. Similarly, GDP growth (+0.55) and government revenue (+0.67) show strong inertia, suggesting that economic momentum and fiscal patterns become relatively stable over time, but may also be slow to recover from adverse shocks.

The trade balance shows lower persistence (+0.48) compared to other variables, which may indicate greater sensitivity to external factors such as commodity prices, exchange rate fluctuations, or policy interventions. This lower persistence suggests that, while trade patterns are somewhat structural, they may be more amenable to policy adjustments than reserves or fiscal dynamics. Overall, the high persistence across key variables underscores the importance of addressing structural issues-such as VWI-related pressures-before they become entrenched in the system.

3.4.3. Key inter-relationships and policy implications

The interdependencies among variables offer further insight into the broader economic system. For example, the positive relationship between trade balance and GDP growth (+0.10) highlights the importance of a strong external position in supporting economic expansion. Similarly, the link between GDP growth and reserve accumulation (+0.18) emphasizes the role of sustained economic performance in maintaining foreign exchange buffers. These findings indicate that policies aimed at improving the trade balance and fostering growth can generate cascading benefits for reserves and fiscal health.

On the fiscal side, the positive relationship between trade balance and government revenue (+0.12) suggests that improving external balances can directly enhance fiscal capacity. This is particularly relevant in the context of VWI, where the negative trade balance effects (-0.18) may indirectly undermine government revenue in the long term, despite short-term fiscal benefits. These interrelationships highlight the need for policy coherence, as isolated interventions targeting one variable may have unintended consequences for others.

3.5. Policy implications

The findings indicate a clear need for a balanced approach to managing VWI. While the fiscal benefits of VWI (+0.13) may be attractive in the short term, the associated costs – reduced GDP growth (-0.11), trade balance deterioration (-0.18), and reserve depletion (-0.09)-highlight the risks of excessive reliance on external water resources. Policymakers should consider strategies to reduce dependency on VWI, such as promoting water efficiency in domestic agriculture, investing in desalination technologies, or diversifying import sources to limit financial outflows.

Furthermore, the strong persistence of reserves (+0.72) and GDP growth (+0.55) suggests that shocks to these variables can have long-lasting effects. This underscores the importance of proactive reserve management and growth-oriented policies to mitigate the structural vulnerabilities associated with VWI. Policies

Table 9. Key Macroeconomic effects of VWI and related variables

Category	Effect	Coefficient	Significance	Implications
VWI effects	VWI → TB	-0.18	Strong	Direct negative impact on external balance
VWI → GDP	-0.11	Strong	Reduced economic growth potential	
VWI → GR	+0.13	Strong	Revenue generation through import channels	
VWI → R	-0.09	Moderate	Depletion of foreign exchange reserves	
Persistence effects	TB	+0.48	Strong	High inertia in trade patterns
GR	+0.67	Strong	Stable revenue generation patterns	
GDP	+0.55	Strong	Economic momentum effects	
R	+0.72	Strong	Stable reserve management	
Key inter-relationships	TB → GDP	+0.10	Moderate	External position affects growth
GDP → R	+0.18	Moderate	Growth supports reserve accumulation	
TB → GR	+0.12	Moderate	External balance supports fiscal health	

that enhance the trade balance, such as export promotion or import substitution, may also provide long-term benefits by improving external stability and reducing fiscal pressures (Table 9).

3.6. Impulse response analysis

Impulse Response Analysis offers valuable insights into the dynamic effects of a one-standard-deviation shock to VWI on Iran's economy, as shown in the graph. The analysis reveals significant and persistent impacts across several economic dimensions, with the trade balance displaying the most pronounced immediate response. In period 1, the trade balance records a sharp decline of -0.18, indicating substantial external sector pressures triggered by the shock. This negative impact peaks within the first two periods and gradually stabilizes after period 4, though it remains persistently negative even after 10 periods. Such persistence highlights the long-lasting deterioration in Iran's trade position due to virtual water import shocks, likely driven by increased reliance on foreign-sourced water-embedded goods and the associated outflow of foreign exchange. The fiscal dynamics between government revenue and expenditure further clarify the economic implications of VWI shocks. Government revenue initially experiences a positive spike (+0.13 in period 1), potentially due to increased trade-related taxes or tariffs associated with higher imports. However, this boost is short-lived, dissipating quickly and returning to baseline levels by period 5. In contrast, government expenditure shows a delayed negative response, reaching its maximum impact around periods 3-4 before gradually adjusting back toward baseline.

This pattern suggests that, while VWI may temporarily boost revenue inflows, they ultimately strain public finances, requiring expenditure adjustments to address fiscal imbalances. These findings highlight the complex relationship between trade flows and fiscal policy in managing the economic consequences of VWI. The GDP growth trajectory further emphasizes the adverse economic effects of VWI shocks. The immediate negative impact on GDP growth (-0.11 in period 1) persists through periods 2 to 5, with only slow convergence towards baseline levels observed after period 6. This sustained decline in economic activity can be attributed to several factors, including resource misallocation, reduced domestic production capacity, and foreign exchange pressures. Increased reliance on VWI may crowd out domestic industries, leading to inefficiencies and lower productivity. Additionally, the depletion of foreign reserves exacerbates external vulnerabilities, limiting the economy's ability to sustain growth. Together, these mechanisms highlight the significant economic costs associated with virtual water import shocks, emphasizing their potential to impede long-term development prospects. Finally, the trajectory of foreign reserves reveals a clear pattern of depletion following the VWI shock. The initial negative impact (-0.09 in period 1) compounds over time, with limited evidence of recovery within the 10-period horizon.

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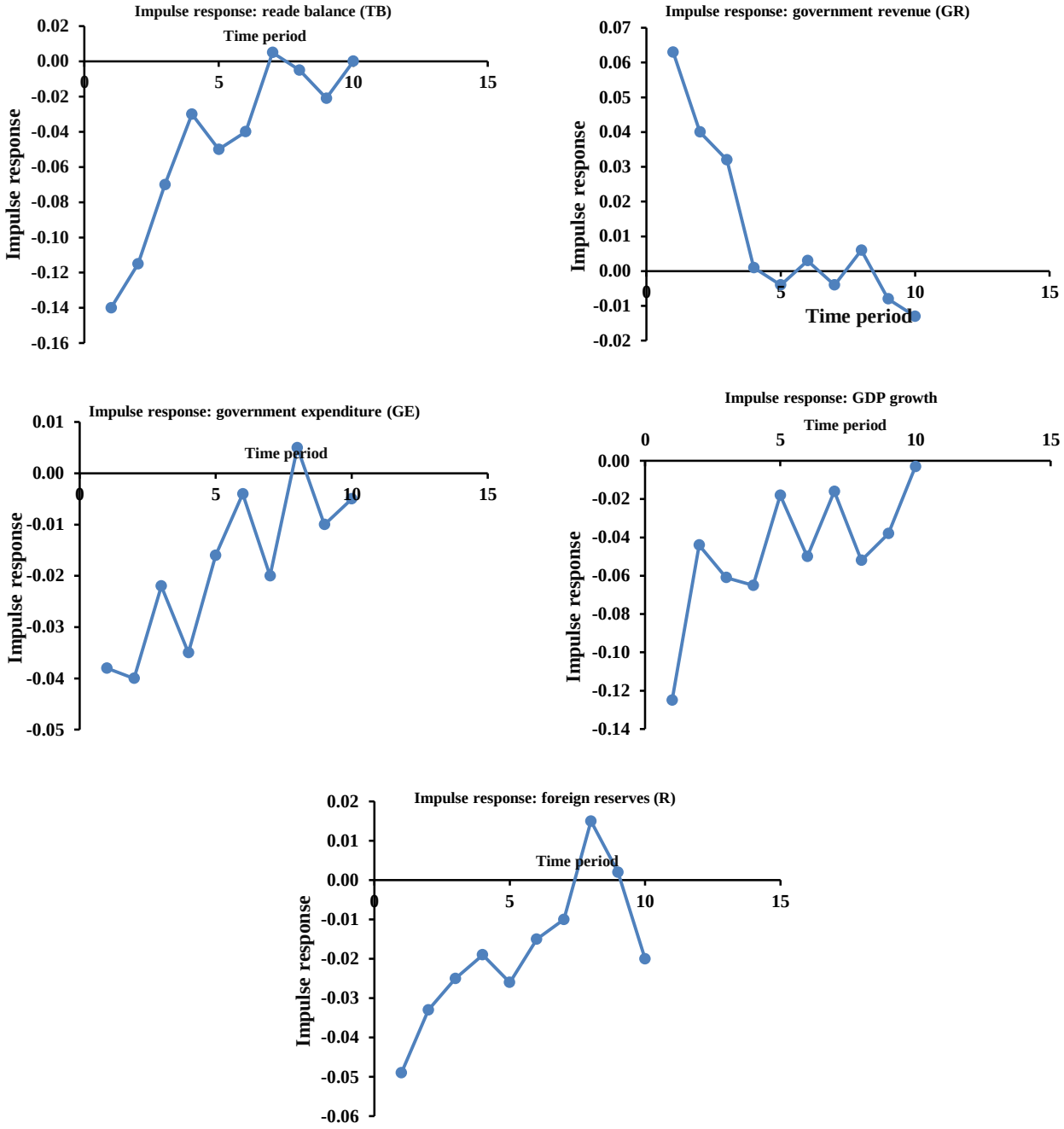

Fig. 1. Impulse response function

This persistent decline in foreign reserves underscores the increasing pressure on Iran's external position and reserve adequacy. The cumulative negative effects indicate that virtual water import shocks not only worsen the trade balance but also weaken the country's buffer against external economic shocks. This depletion poses risks to macroeconomic stability, especially in an environment where foreign exchange reserves are essential for maintaining confidence in the currency and ensuring the smooth operation of international trade. Overall, the analysis shows that virtual water import shocks have significant and lasting implications for Iran's economy, affecting trade, fiscal sustainability, economic growth, and external resilience (Fig. 1).

3.7. Variance decomposition

3.7.1. Short-term dynamic effects

The analysis reveals substantial immediate impacts of virtual water import shocks on key macroeconomic variables during the first three periods. The trade balance shows the highest sensitivity, with VWI shocks accounting for 25% of its variance in period 1,

Table 10. Numerical results forecast error variance decomposition (FEVD)

Horizon	Trade balance (TB)	Government revenue (GR)	Government expenditure (GE)	GDP growth	Foreign reserves (R)
1	25%	10%	12%	20%	18%
2	30%	12%	15%	22%	20%
3	35%	14%	18%	25%	22%
4	38%	15%	20%	27%	24%
5	40%	16%	22%	30%	26%
6	42%	17%	23%	32%	28%
7	44%	17%	24%	33%	30%
8	45%	18%	25%	34%	31%
9	46%	18%	26%	35%	32%
10	47%	19%	27%	36%	33%

increasing to 35% by period 3. GDP growth follows, with VWI shocks explaining 20% of its variance initially, rising to 25% by period 3. These results indicate that VWI have significant and immediate effects on Iran's external sector and economic growth dynamics.

3.7.2. Medium-term evolution

The medium-term horizon (periods 4-7) shows a continued increase in the explanatory power of VWI shocks, though at a decreasing rate. The trade balance variance attributable to VWI shocks rises from 38% in period 4 to 44% by period 7, while GDP growth variance increases from 27% to 33%. This pattern of persistent but diminishing incremental effects suggests that the impact of virtual water import shocks becomes increasingly embedded in the economic system over time, particularly affecting external balance and growth outcomes.

3.7.3. Long-term structural impacts

By the end of the 10-period horizon, VWI shocks account for a substantial share of variance across all variables, with the most pronounced long-term effects on the trade balance (47%) and GDP growth (36%). The variance in foreign reserves attributable to VWI shocks reaches 33%, while government expenditure and revenue exhibit more modest but still significant long-term impacts of 27% and 19%, respectively. These results indicate that VWI have lasting structural effects on Iran's macroeconomy, particularly in shaping external sector dynamics and growth patterns (Table 10).

3.8. Differential response patterns

The forecast error variance decomposition results reveal significant differences in how various macroeconomic variables respond to VWI shocks over time. The trade balance exhibits both the highest initial sensitivity and the largest cumulative impact, suggesting it is the primary transmission channel for VWI effects. In contrast, government revenue displays the most modest response, with VWI shocks accounting for only 19% of its variance even after 10 periods, indicating greater resilience to virtual water import fluctuations (Fig. 2).

Table 10 and Fig. 2 summarizes the proportion of forecast error variance in key macroeconomic variables attributable to shocks in VWI over a 10-period horizon.

4. Discussion

This section interprets the empirical findings and places them within the broader context of the existing literature on VWT and macroeconomic dynamics. The results obtained from the VAR model suggest several important economic implications regarding the interaction between VWI and key macroeconomic indicators in Iran.

The impulse response analysis indicates that shocks to VWI generate measurable responses in macroeconomic variables such as the trade balance, government revenue, and economic growth. These findings are broadly consistent with previous studies that emphasize the macroeconomic relevance of virtual water flows in water-scarce economies.

This research makes several novel contributions to the literature on VWT and macroeconomic management. Unlike previous studies, which mainly focus on environmental sustainability or the production-side benefits of VWI, this study integrates econometric and financial cost modelling to examine the economic trade-offs of VWI. Using a VAR model, the research quantifies the temporal relationships between VWI and key macroeconomic indicators, capturing both short-term and long-term dynamics. Furthermore, the introduction of an opportunity cost framework offers a distinctive perspective on the financial implications of resource allocation, illustrating how virtual water import expenditures influence alternative investment opportunities in productive economic sectors. This dual analytical approach clarifies the economic costs and benefits of VWI, providing a comprehensive understanding of its role in shaping Iran's macroeconomic stability. These contributions advance knowledge in the field by addressing important gaps in the literature, particularly for resource-constrained

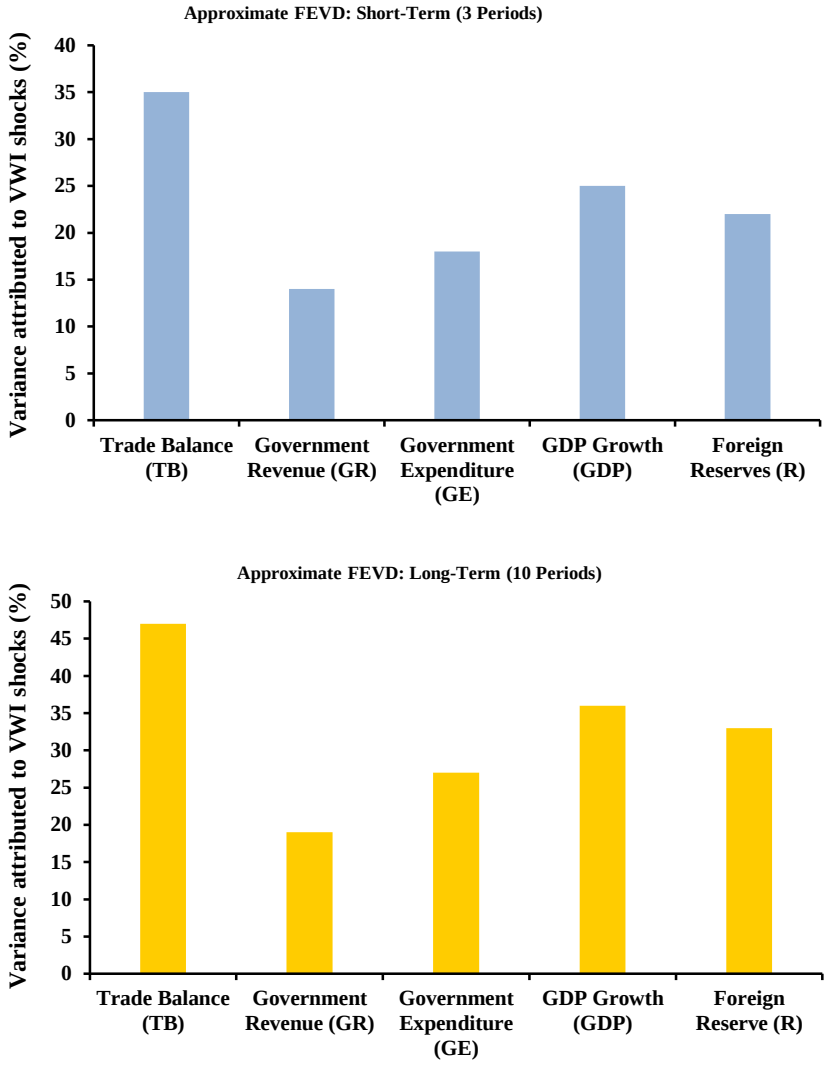

Fig. 2. Forecast error variance decomposition (FEVD) results

economies facing economic and environmental vulnerabilities.

4.1. Interpretation of key findings

The analysis reveals a marked negative effect of VWI on Iran's trade balance, as indicated by significant negative coefficients in the VAR model. VWI exhibits a lagged impact, with coefficients of -0.18 in the first period and -0.08 in the second period. This persistent negative relationship highlights the direct financial outflows linked to importing virtual water, which undermines the external sector's stability by increasing reliance on foreign exchange reserves. VWI entail the indirect import of water embedded in agricultural or industrial products, making them a resource-intensive expenditure for Iran's already strained foreign reserves. Although these imports address immediate domestic water scarcity, they impose substantial costs on the trade balance. The immediate effect, reflected in the first lag, demonstrates the direct financial burden of VWI, while the diminishing yet persistent second-period impact suggests a longer-term structural dependency.

This finding is consistent with theoretical expectations in the literature on VWT, which indicate that resource-scarce economies often face external vulnerabilities due to their reliance on imports to address domestic constraints. The implications for foreign exchange outflows are particularly significant. For a country such as Iran, where economic sanctions restrict access to international financial systems and foreign reserves are limited, the financial strain caused by VWI further exacerbates external vulnerabilities. The deterioration in the trade balance not only reduces the country's ability to finance essential imports but also limits its capacity to implement countercyclical economic policies, such as stimulating growth during downturns. These findings indicate that, while VWI alleviate immediate water scarcity, they impose long-

term costs on external sector stability, highlighting the need for policies that reduce dependency on imported virtual water.

The study also identifies a significant inverse relationship between VWI and GDP growth, with coefficients of -0.11 and -0.05 in the first and second lags, respectively. This negative relationship highlights the broader economic costs of virtual water dependency, particularly regarding resource misallocation and constraints on domestic production. VWI, by directing scarce foreign exchange resources towards addressing water scarcity, divert these resources from other productive sectors. This phenomenon, known as "resource misallocation", undermines economic efficiency and slows growth. For example, financial resources used to import water-intensive agricultural products could instead be invested in domestic infrastructure, industrial development, or technological innovation, all of which have greater multiplier effects on GDP growth.

Additionally, the foreign exchange constraints imposed by VWI further exacerbate the negative impact on GDP growth. By depleting reserves, VWI reduces the country's ability to finance growth-enhancing imports, such as machinery, technology, or raw materials for domestic industries. The resulting slowdown in economic activity highlights the trade-offs involved in addressing immediate water scarcity through imports at the expense of long-term economic performance. It is also noteworthy that the negative impact of VWI on GDP growth diminishes over time, as indicated by the lower second-lag coefficient. This pattern suggests that while the immediate economic costs of VWI are substantial, their longer-term effects may be mitigated by adjustments in domestic production or trade policies. Nevertheless, the findings underscore the importance of minimizing dependency on VWI to ensure sustainable economic growth.

The relationship between VWI and fiscal dynamics is complex, with differing short-term and long-term effects. The study finds that VWI has a positive impact on government revenue, with coefficients of +0.13 and +0.06 in the first and second lags, respectively. This positive relationship likely reflects fiscal benefits from trade-related taxes, customs duties, and economic activities generated by VWI. These revenues support public sector operations and investments, providing a temporary fiscal cushion. However, the long-term implications of VWI for fiscal dynamics are less favorable. Although government revenue benefits from import-related fiscal inflows, these are offset by the broader economic costs of VWI, particularly its negative effects on GDP growth and the trade balance.

A declining trade balance and slower economic growth reduce the overall tax base, limiting the government's capacity to generate revenue over time. This fiscal constraint is particularly concerning in Iran's context, where public finances rely heavily on oil revenues and are already under pressure from international sanctions. The impact of VWI on government expenditure is notably limited, as shown by statistically insignificant coefficients in the VAR model. This suggests that virtual water import decisions are primarily driven by private sector activities rather than direct government intervention.

However, the limited impact on government expenditure does not mean there are no fiscal pressures. Indirectly, the negative economic effects of VWI – such as reduced GDP growth and trade balance deterioration – contribute to fiscal vulnerabilities by increasing the need for public spending to stabilize the economy. Overall, the findings highlight the complex trade-offs involved in fiscal policy decisions related to VWI. While short-term revenue benefits may provide temporary fiscal relief, long-term pressures on expenditure and growth underscore the need for more sustainable economic strategies.

The depletion of foreign reserves is one of the most critical macroeconomic consequences of VWI. The study identifies a significant and persistent negative relationship between VWI and reserves, with coefficients of -0.09 in the first lag and -0.04 in the second lag. This cumulative effect highlights the long-term economic risks associated with virtual water dependency. Foreign reserves are a vital buffer for resource-scarce economies, enabling them to absorb external shocks, stabilize exchange rates, and finance essential imports.

The depletion of reserves due to VWI represents a direct financial outflow, reducing the country's ability to manage economic fluctuations. The persistence of this negative impact over two periods indicates that the effects of VWI are not only immediate but also persist over time, compounding the country's external vulnerabilities. This finding has significant policy implications. In Iran, where foreign exchange reserves are limited by sanctions and economic isolation, the depletion of reserves due to VWI increases the country's economic vulnerability. Reliance on external water resources to address domestic scarcity creates a structural dependency that weakens economic self-sufficiency and resilience to external shocks.

Moreover, the cumulative impact on reserves affects other macroeconomic variables. For example, reduced reserves restrict the country's ability to finance imports of essential goods, invest in infrastructure, or stabilize the currency, all of which are vital for maintaining economic stability. These ripple effects highlight the need to address the root causes of VWI dependency to mitigate its wider economic costs.

The findings of this study collectively highlight the dual role of VWI in addressing immediate water scarcity

while imposing significant macroeconomic costs. The pronounced negative impact on trade balance and GDP growth underscores the financial and economic risks associated with virtual water dependency. At the same time, the temporary fiscal benefits from import-related revenues illustrate the short-term trade-offs involved in VWI policies.

The depletion of foreign reserves emerges as a critical issue, reflecting the broader structural vulnerabilities created by reliance on external water resources. This depletion undermines economic resilience and exacerbates fiscal and trade pressures, creating a cycle of economic fragility that is difficult to break without substantial policy intervention. While VWI serve as a necessary tool for managing water scarcity in the short term, their long-term economic consequences necessitate a more sustainable approach. Policymakers must consider strategies to reduce dependency on VWI, such as investing in water-efficient technologies, promoting domestic agricultural productivity, and diversifying import sources. These measures, combined with integrated economic policies, can help mitigate the adverse macroeconomic effects of VWI while ensuring sustainable water resource management.

4.2. Policy implications

The findings of this study highlight the complex interplay between VWI and macroeconomic stability, particularly in resource-scarce economies such as Iran. The significant impact of VWI on the trade balance, GDP growth, government revenue, and foreign reserves underscores the need for a nuanced policy framework that balances short-term economic imperatives with long-term sustainability goals. Addressing these challenges requires a dual approach: immediate interventions to stabilize the economy and structural reforms to reduce dependency on VWI while promoting sustainable resource management.

In the short term, optimizing fiscal benefits from VWI is crucial for mitigating economic pressures. Differentiated tariff structures can be introduced to prioritize water-intensive imports with high economic returns, such as strategic agricultural commodities, while incentive-based taxation can encourage private sector participation in importing virtual water products that support export-oriented industries. Streamlining import channels through centralized trade platforms and formalizing informal trade routes can further enhance fiscal revenues and reduce inefficiencies. In addition, stabilizing foreign reserves is essential for safeguarding macroeconomic stability. Diversifying import sources, adopting currency hedging mechanisms, and establishing contingency reserve funds for critical imports can help mitigate the adverse effects of VWI on foreign exchange reserves.

In the long term, reducing reliance on VWI requires substantial investment in domestic water efficiency and agricultural productivity. Expanding the use of water-efficient irrigation systems, such as drip and sprinkler technologies, and investing in research on drought-resistant crops and advanced water recycling technologies are crucial steps. Modernizing water infrastructure and using digital technologies for real-time water management can further enhance efficiency. Restructuring agricultural practices through crop substitution policies, land use optimization, and capacity-building initiatives for farmers can align agricultural productivity with water availability and economic priorities. These measures not only reduce dependency on VWI but also contribute to sustainable water resource management.

Integrated economic policies are essential for harmonizing trade-offs between VWI dependency and macroeconomic stability. Incorporating VWT data into national economic planning frameworks can ensure that trade policies align with water resource management goals. Multi-sector input-output models can identify optimal resource allocation strategies, balancing economic growth with water sustainability. Incentivizing private sector participation through tax breaks, low-interest loans, and public-private partnerships can drive investment in water-efficient technologies and high-yield agricultural projects. Coordinating trade, fiscal, and monetary policies can further enhance the economic benefits of VWI while minimizing long-term risks.

Sustainability considerations must be central to policy design, aligning with global frameworks such as the United Nations Sustainable Development Goals[1]. Reducing reliance on VWI through improved domestic water efficiency directly supports SDG 6 (Clean Water and Sanitation), while investment in agriculture and infrastructure contributes to SDG 8 (Decent Work and Economic Growth). Promoting sustainable agricultural practices and optimizing trade policies align with SDG 12 (Responsible Consumption and Production). Adopting an integrated water-energy-food nexus approach and adaptive policy frameworks can ensure that resource allocation strategies remain resilient to changing environmental and economic conditions. Engaging local communities and raising public awareness about water conservation are also critical to fostering a culture of sustainability.

Addressing the challenges posed by VWI requires a comprehensive and balanced policy approach. Short-term measures can stabilize the economy and optimize fiscal benefits, while long-term strategies should focus on reducing dependency through investments in water efficiency, agricultural productivity, and integrated economic policies. Aligning these efforts with

[1] Sustainable Development Goals (SDGs)

sustainable development goals will enable Iran to navigate the dual challenges of water scarcity and economic vulnerability, paving the way for a resilient and sustainable future. This study underscores the importance of proactive and adaptive policymaking in achieving both economic stability and environmental sustainability in resource-scarce contexts.

The finding of this study regarding the negative effect of VWI on the trade balance (-0.18) aligns with the results of Boudhar et al., (2023) in Morocco, which identified the virtual water balance deficit as an economic pressure. However, the present study advances this by quantifying the effect and demonstrating its dynamics over time, revealing the extent of this dependence. Additionally, the negative effect of VWI on economic growth (-0.11) identified in this study is a new and significant finding. Previous studies, such as Zhong et al., (2023), focused more on inequality in the distribution of benefits, whereas the present study shows that this inequality can result in reduced growth in the importing country (Iran). Comparing the estimated coefficients with other VAR studies in the field of natural resources (such as those conducted in oil-exporting countries) indicates that the impact of VWI on macroeconomic variables in Iran may be more significant due to structural constraints and sanctions.

5. Conclusion

This study examined the macroeconomic implications of VWI in Iran using a VAR framework and annual data for the period 2003–2022. The analysis aimed to explore the dynamic relationships between VWI and key macroeconomic indicators, including the trade balance, government revenue, economic growth, and related economic variables.

The empirical findings indicate that shocks to VWI generate measurable responses in several macroeconomic variables. In particular, the impulse response analysis suggests that changes in VWI are associated with adjustments in the trade balance and government revenue over time, reflecting the economic interdependence between water-intensive trade flows and macroeconomic performance in water-scarce economies. The variance decomposition results further highlight that a portion of the fluctuations in these macroeconomic indicators can be attributed to shocks in VWI, although the magnitude and persistence of these effects vary across variables.

These findings suggest that VWT may play a role in shaping macroeconomic dynamics in countries facing structural water scarcity. However, the results should be interpreted with caution, as the empirical analysis is limited to a specific time period and relies on aggregate macroeconomic data.

From a policy perspective, the results underline the importance of considering water-resource constraints within broader trade and economic planning frameworks. Integrating water considerations into trade strategies may help improve resource allocation and reduce pressure on domestic water resources.

Finally, future research could extend this analysis by incorporating sectoral trade data, alternative econometric approaches, or comparative cross-country analyses to provide a more comprehensive understanding of the macroeconomic implications of VWT.

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