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Mathematical Modeling of Drinking Water Losses Management Case Study – Cairo - Egypt

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Abstract:
Water, As A Precious natural resource, necessitates sustainable management to minimize wastage. Excessive leakage, particularly in regions confronting water scarcity such as Egypt, directly undermines environmental objectives and principles of cost recovery. Effective water management is pivotal for reducing losses and optimizing efficiency. Accurate measurement of water production and distribution is essential to identify losses and assess water utilities' performance. This data aids in pinpointing the root causes of losses, whether physical or commercial, facilitating targeted reduction strategies. Forecasting supply-demand balance is critical for planning water networks and treatment facilities. Detailed infrastructure information enables decision-makers to discern areas experiencing water shortages and those with surplus resources. Our aim is to probe the causes of water losses in Cairo's drinking water network, the capital of Egypt, and propose managerial solutions.

Operational efficiency relies on minimizing labor, material, and energy costs. Water loss poses a significant operational challenge, as components of non-revenue water can significantly impact utilities' financial stability. The IWA Water Balance offers a standardized approach to water audits, facilitating a comprehensive analysis of water production, storage, and distribution. This analysis aids in quantifying the magnitude of the water loss problem and prioritizing corrective actions based on revenue and non-revenue water components.

The Cairo Water Company is entrusted with producing 5.5 million cubic meters of purified drinking water per day from 11 treatment plants, serving a network spanning 13,307 kilometers and supported by 20 maintenance centers. With a focus on serving 1.1 million citizens in compliance with Egyptian regulations, our study encompasses various metrics, including billed and unbilled consumption, unauthorized usage, and metering inaccuracies, to calculate commercial losses. Additionally, we evaluate main and storage leakages, as well as service connection leakages up to the customer meter, to determine technical losses. Through a mathematical module, we compute non-revenue water (NRW) and infrastructure leakage index (ILI) metrics. Performance indicators are utilized to assess the effectiveness of water utilities in managing losses and asset maintenance.

Our designed module empowers decision-makers to evaluate and enhance asset methodologies for water loss management.

Keywords: Physical losses, Commercial losses, The billed metered consumption, The billed unmetered consumption, Unbilled authorized metered consumption, Unbilled authorized unmetered consumption, Unauthorized consumption, Non –revenue water, Infrastructure leakage index, Pressure management (PM), Active leakage control (ALC).

Literature Review:

Access to drinking water is essential for human survival and is vital for the economic development, social development, ecological conservation, and health security of developing countries , Increasing pressure on water supply due to environmental pollution and climate change has resulted in urban water scarcity, One of the contributing factors to drinking water scarcity is water loss or non-revenue water, NRW loss management allows water utilities to expand and improve service, enhances utility financial performance, It also increases climate resilience and reduces energy consumption by utilities, thus reduction of NRW loss translates into a sustainable water management system. For water utility managers to develop a sound NRW loss management strategy, it is essential to identify critical factors influencing NRW loss from the water utility distribution system [1].

Water losses and the associated financial losses represent a serious problem for water supply companies all over the world, the losses can be classified into (Physical losses, and commercial losses). The physical losses are: losses in the treatment plant during washing process, in the storage reservoirs and booster pump station, in the distribution network, physical losses or real losses comprise leakage from all the part of the system and overflows reservoirs they are caused by poor operations and maintenance, the lack of active leakage control, and poor quality of underground assets [2]. while commercial losses are at times called Apparent losses or Non-technical losses, which include all types of inaccuracies associated with customer metering as well as data handling errors (meter reading and billing), plus unauthorized consumption (theft or illegal use), commercial losses or apparent losses are caused by customer under registration, data handling errors, and theft of water in various forms [3], it can be defined as the amount of (Unbilled authorized consumption & Unauthorized consumption):

- Unbilled authorized consumption includes water used by the utility for operational purpose, water used for firefighting, and water provided for free to certain consumer groups.
- Unauthorized consumption of Water what is popularly known as illegal usage of water, including illegal water withdrawal from hydrants (for example for construction purpose), illegal connection, bypass to consumption meters or meter tampering.

Although it is widely acknowledged that NRW levels in developing countries are often high, most water utilities do not have adequate monitoring system for assessing water losses and many countries have lock national reporting system, normally around 90% of water that is physically lost from leaks cannot be seen on the surface these leaks might eventually become visible after many years. Large volumes of water are lost every year if the water utility department doesn't practice a policy of efficient and intensive leakage control especially in old infrastructure [4], The way an organization manages its assets, should address the challenges in the level of service, and reduce water losses, and determines when and how to maintain or replace those assets and how the assets should be operated. Adequate asset management plans are necessary because poor asset management leads to: High rate of water losses, random maintenance, weak pricing strategies [5].

Creating a unified mathematical model that can be applied to all water systems and use it to follow up on the NRW reduction ,all the data required to Calculate the Percentage of NRW is available in water company Except the term of unauthorized consumption and Meter Failure ,the Term of unauthorized consumption can be predictable by Establish several model depending on the Following properties: the level of water charges, 2) the characteristics of residents in the district, 3) the condition of road pavement, 4) the material of buried water pipes (whether it is a material that is easy to make illegal connections), etc. Conduct intensive investigation in the model districts and calculate. It may be used to predict other districts with similar district characteristics. And for the term of Meter Failure: if the number of installed meters and the number of repaired meters are available it can easily be figuring the overall failure rate, In Japan (Osaka City) the percentage of failure meters found when the meters are replaced due to the expiration dates is about 0.05% of the total number of replacements. The estimation of the number of failure meters is basically based on the past record. In the case of Japan, the JIS (Japan Industrial Standards) stipulates that the measurement error of water meters is ± 5% in the small flow rate range and ± 2% in the large flow rate range [3], it is important to create a mechanism for appropriate replacement frequency and reuse of water meters in order to reduce the meter failure rate.

The amount of water lost from distribution systems is huge in the world and is estimated at 48 billion m3 per year [9]. High levels of water losses result from poor management and poor condition of distribution systems [10]. The increase in water losses forces water supply companies to implement systems for control and evaluation of water losses, make organizational changes and to develop and implement modernization programs in order to improve the technical condition of water supply networks. In every company, a reliable analysis of water losses should precede decisions concerning the repair or modernization of the water supply system [11]. Due to the optimization of water production costs, rational reduction of water losses must be a priority task for water supply companies. By reducing the losses, plants can reduce the costs of the current network exploitation and save on the investment costs. it has been emphasized in numerous studies [12]. For water supply companies, the immediate removal of leakages is cost-effective and provides measurable economic and ecological benefits. The reduction of leakages helps protect the limited water resources, minimize production of water treatment products and energy consumption and other costs resulting from leakages, such as subsidence of buildings or road collapses, and even costs incurred due to traffic jams caused by the elimination of the effects of water supply failures [13]. water loss is defined as the quantity of water different between supply and consumption through the distribution system, The main benefits of reducing water losses are executed as:1) reducing pumping and water treatment costs, 2) increase in revenue water, 3) delay of investments for new water infrastructure, 4)postponing the need for new water resources, 5) protection of water quality and reducing the risks of water borne diseases, 6) reduction in frequency of pipe bursts and water cuts , Nazif et al. asserted that pressure management is an effective technique for leakage reduction. These authors emphasized the relationship between leakage and pressure. They described the procedure for controlling the hydraulic pressure in the water distribution system by maintaining the water levels in the storage tanks to adjust to the variations in the water demand. To minimize the leakage level, the authors used an optimization model to evaluate the optimal hourly water level variations in the storage tank to reduce the pressure in water supply system with regards to the required water amount, water level in reservoir, and the elevation of observed points in the water supply network [14], 7) service life extension of pipes and other equipment and 8) improving satisfaction of water subscribers. Understanding and quantifying NRW and water losses components is the first step for management of urban water losses. The International Water Organization (IWA) has developed a water audit methodology ("Water Balance") accounting for all water entering a water supply system, which has been accepted worldwide. The IWA Water Balance provides a standardized approach using a common international terminology based on best practice for many countries, the analysis of losses should be the basis for taking modernization and repair measures, thus reducing the costs connected with production and distribution of water. The International Water Association (IWA) proposes four methods of performing such activities: active leakage control, speed and quality of repairs, pressure management, and pipe materials management in order to limit the extent of water losses in this study we designed a mathematical module based on the water audit Handling the reduction of water losses is a long-term job, even as long as the utility still exists. The losses of water can't be eliminated at all, but can be lowered to the lowest possible level. This long-term work need handling such as monitoring and evaluation, consists of planning stage, implementation stage, monitoring and evaluation, and corrective action. All these stages are a continuous cycle until the target of water losses is achieved. (fig1).

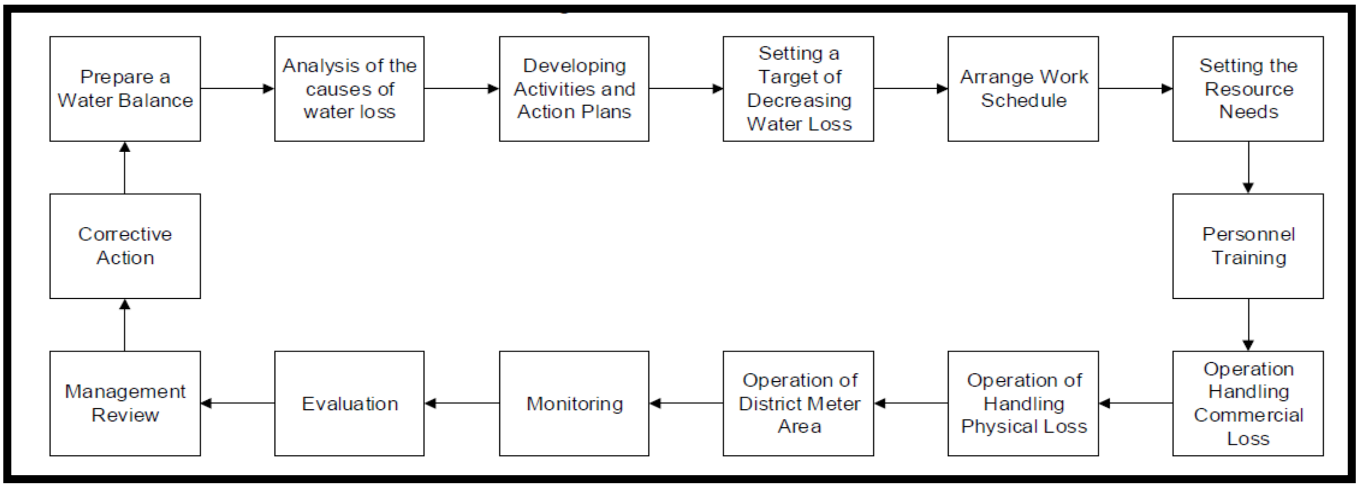

Fig (1): Reduced water losses handling cycle (adopted from Ali etal, 2018).

The IWA group has also identified four intervention strategies to reduce real water losses explained as follow.(fig2)

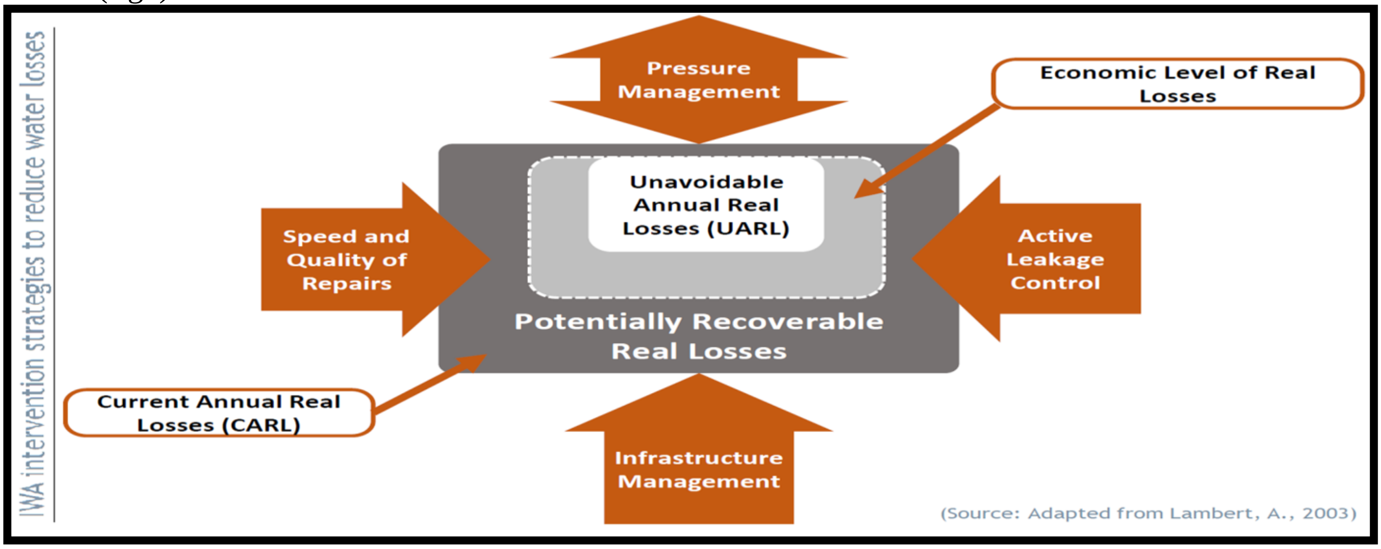

Fig (2): The IWA intervention strategies

1- Pressure management (PM): It is the practice of managing system pressures to the optimum levels of service ensuring sufficient and efficient supply, while reducing unnecessary or excess pressures, eliminating transients and faulty level controls, and reducing the impact of theft.

2- Active Leakage Control (ALC):It is defined as the monitoring of network flows on a regular basis to identify occurrence of new leaks or bursts earlier, this has two stages leak monitoring and localization, and Leak location and pinpointing, Leak monitoring and localization aims to identify the area of the network in which leakage is occurring in order to prioritize field survey, A popular approach is to divide the network into District Metered Areas (DMAs) by shutting valves permanently and installing meters equipped with telemetry data loggers, allowing continuous monitoring of zone consumption from which an estimate of leakage can be made.

3- Speed and quality of repairs: Known leaks which have been found by active leakage control, these must be repaired at some point in time. However, the aim should be to avoid excessive repair time.

4-Infrastructure management: pipeline asset management, selection, installation, maintenance, renewal and replacement, in areas with high burst frequencies and /or high rates of rise of leakage an economic decision Can be taken to continue repairing the assets or whether to replace them.

The four control strategies interact with each other. Experiences over the last 13 years clearly show that reduction of excess pressure and pressure transients has a major beneficial influence on the other three control strategies, Nowadays it is widely accepted internationally that Pressure Management reduces leak flow rates, and reduces frequency of leaks in older mains and services, which in turn can extend infrastructure life.

It should be emphasized that the analyzed utilities have been involved in comprehensive initiatives aimed at reducing water leakages, resulting in a substantial reduction in water losses. GIS monitoring systems and data bases are particularly helpful in reducing water losses. The basis of the activities is monitoring of flow and pressure in water supply networks and active leakage control. Network zoning with simultaneous observation of minimum night-time flows allows for preliminary location of the failure. Equipping companies with special leakage detection devices such as geophones, stethophones or correlators enables quick detection of leakages. The next step is to replace water meters with more and more accurate ones and to implement radio reading of water meters. All analyzed utilities perform systematic replacement of old steel and cast iron pipes which cause a large number of leakages that are often difficult to identify, thus leading to water losses. researchers dealing with water loss management in distribution systems and providing a road map for future research, Previous research identifies physical, technical, and environmental factors as drivers of

NRW loss, with less focus on managerial aspects such as economic or financial

A current major challenge for Egyptian utilities is how managerial and physical characteristics impact NRW loss. Hence, more studies are needed to bridge this knowledge gap to improve water management and decrease NRW loss.

Methodology:

To carry out the study objective, the following interrelated hierarchy steps were Implemented as shown below:

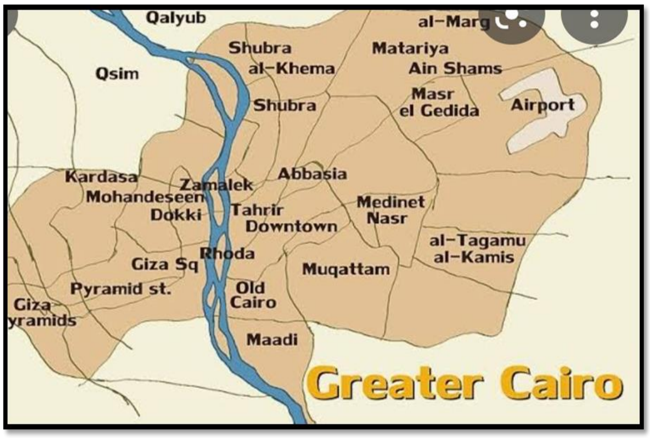

Figure (3): The management of water losses methodology.

1. Field visit (collecting data):

Water Balance department of Cairo Water utility, the service Area of the Cairo Water (Misr elgedida, Ziton, Mataria, Ain - Shams, Shubra el –Khema, Shubra, Tahrir, Zamalek, Dokki, Mohandessen, Mediante Nasser,)

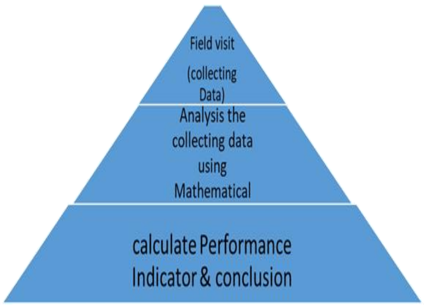

Fig (4): Service Area of the Cairo Water Utility

Tab (1) The Collecting Data

	Item	Value (m3/year)
First study year data	Water Supplied to the System	11273 *10^3
	Billed authorized consumption	9358*10^3
	Unbilled Authorized consumption	141 * 10^3
	Unauthorized consumption	28 *10^3
	Customer reading inaccuracies	390*10^3
Second study year data	Water Supplied to the System	1.75*10^12
	Billed authorized consumption	1.32*10^12
	Unbilled Authorized consumption	.0218*10^12
	Unauthorized consumption	.0043*10^2
	Customer reading inaccuracies	.0528*10^12

2. Analysis The Collecting Data using the Mathematical module:

- Stages of Mathematical module development: (The IWA water balance international terminology was taken as the base concept to design the proposed module):
- Module development: (Program is Visual Studio, programming language is Visual Basic, Database SQL Structured Query Language).
- Module calibration: Trying the Module on real dataset collected from the Cairo water utility at the first year study.
- Module verification: Trying the Module on another Dataset for another financial year for the Cairo water utility.
- Module application: Apply the Model Show result &Make Recommendation.

Fig (5) IWA Water Balance approach

3. Calculate the performance indicator:

- Infrastructure leakage Index(ILI):
- the Infrastructure Leakage Index (ILI) provides guidance as to how well real losses are being managed (in terms of repairs, active leakage control and infrastructure management, the current operating pressure), So even if a low ILI is being achieved, there may still be opportunities to reduce annual real losses by improved pressure management, The Infrastructure Leakage Index (ILI) is the ratio between the actual volume of physical losses and the minimum (unavoidable) level of leakage it is defined as the minimum achievable annual volume of physical losses MAAPL (liters/day) And it calculated from the following equation which acceptably from IWA organization:
- (liters/day)10 = (18 × Lm + 0.8 × Nc + 25 × Lp) × P
- where MAAPL = minimum achievable annual volume of physical losses; Lm = mains length(km); Nc = number of service connections; P = average pressure (m); and Lp = small correction factor.
- Non-Revenue Water NRW: The difference between the amount of water a water utility pumps into the distribution system and the amount of water that is billed to its consumers is called Non-Revenue Water (NRW), And it calculated from the following equation:

  NRW=(Unbilled authorized consumption+ Apparent losses+ Real losses).

Analyzing the Results from the Mathematical Model and prepare Recommendations due to the results as the World Bank Institute (WBI) Guidelines. And classified into Bands A to D, and appropriate recommended actions are as follows:

Table (2) limit of band classes based on IWA

Developing Countries ILI range	Developed Countries ILI range	BAND	Calculated ILI for this System	General description of Real Loss Management Performance Categories for Developed and Developing Countries
Less than 4	Less than 2	A	1.3	Further loss reduction may be uneconomic unless there are shortages; careful analysis needed to identify cost-effective improvement
4 to < 8	2 to < 4	B		Potential for marked improvements; consider pressure management, better active leakage control practices, and better network maintenance
8 to < 16	4 to < 8	C		Poor leakage record; tolerable only if water is plentiful and cheap; even then, analyze level and nature of leakage and intensify leakage reduction efforts
16 or more	8 or more	D		Very inefficient use of resources; leakage reduction programs imperative and high priority

Results and Discussion:

During the initial assessment, Cairo Water Company was categorized as (A) with an NRW of 17%. In the subsequent evaluation, it was reclassified as (D) with an NRW of 21%, according to the World Bank Institute (WBI) Guidelines. These findings indicate a significant inefficiency in resource utilization, underscoring the urgent need for leakage reduction programs, which should be prioritized.

The reduction of losses not only enhances the economic and financial viability of water utilities but also contributes to environmental protection and public health by ensuring water quality control. It maximizes water supply reliability and affordability, making it a shared responsibility requiring heightened public awareness.

Cairo Water Company should prioritize the replacement of aging steel and cast iron pipes, which are prone to numerous leakages that are often challenging to detect, thereby leading to water losses. Upgrading water meters to more accurate devices and implementing radio reading systems are essential steps. Additionally, deploying advanced leakage detection equipment is crucial for minimizing water losses.

Despite the absence of legislation regarding maximum allowable losses in water supply systems, many companies set targets ranging from 8 to 10%. It is believed that further reduction to 6–8% is achievable but requires substantial investment in effective systems. Therefore, water supply companies must develop optimal loss reduction strategies to minimize losses to the economic level.

Conclusion and Recommendation:

This research introduces an enhanced methodology for evaluating water utilities' management of water losses and asset management. Water authorities should adopt a virtuous cycle where investments in reducing non-revenue water (NRW) lead to increased revenues and decreased operational costs. This creates a positive feedback loop, enabling further investments in operational improvements and NRW reduction programs.

Based on examinations and literature review, the following conclusions emerge:

A. Reducing water losses and the associated energy intensity of water production and supply are essential for achieving sustainable water supply. Monitoring system operation and accurate flow and pressure measurements are fundamental for assessing water losses and system energy efficiency accurately.

B. Water supply companies should develop tailored programs to reduce water losses and energy consumption based on local conditions and company potential, given the unique nature of design solutions and system operation.

C. Examinations of water losses in the studied companies' systems demonstrate the effectiveness of implemented measures. Active leak control, improved work organization, monitoring, pressure regulation, and pipe overhauls have contributed significantly to limiting water losses.

D. Companies should aim to reduce water losses to the economic leakage rate specified for the water supply system. Determining the economic level of leakage requires conducting an economic analysis considering water intake, treatment, distribution costs, as well as costs associated with leak control and disposal.

E. Raising awareness and increasing knowledge about leakage management are crucial for mitigating potential negative impacts of leakage.

Achieving leak-free distribution systems is not a realistic technical or economic goal. Even in well-operated systems where considerable attention is paid to leakage management, a low level of leakage is inevitable. Sustainably managing low leakage levels necessitates a comprehensive understanding of the intricate interactions between various parameters and the influence of past and present management decisions.

Definitions:

Physical losses:

physical losses or real losses comprise leakage from all the part of the system and overflows reservoirs such losses in the treatment plant during washing process, in the storage reservoirs and booster pump station, in the distribution network, they are caused by poor operations and maintenance, the lack of active leakage control, and poor quality of underground assets.

Commercial losses:

losses are caused by customer under registration, data handling errors, and theft of water in various forms, it can be defined as the amount of (Unbilled authorized consumption & Unauthorized consumption).

Unbilled authorized consumption:

Includes water used by the utility for operational purpose, water used for firefighting, and water provided for free to certain consumer groups.

Unauthorized consumption:

Any unauthorized use of water may include illegal water withdrawal from hydrants (for example for construction purpose), illegal connection, by pass to consumption meters or meter tampering.

Real losses :

Is the summation of (leakage on mains, leakage and overflows at storage & leakage on service connection up to point of customer metering).

Non-revenue water:

Is the summation of Unbilled authorized consumption, Apparent losses& Real losses .

Infrastructure Leakage Index:

is the ratio between the actual volume of physical losses and the minimum unavoidable level of leakage.

Pressure management (PM): It is the practice of managing system pressures.

Active Leakage Control (ALC): It is defined as the monitoring of network flows on a regular basis.

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