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# Hydro-Economic Inventory Models for Planning and Evaluation of Farming Water Efficiency in a Semi-Arid Watershed of Kenya

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**ABSTRACT**

Water scarcity and its unsustainable use are threatening farming efficiency in most "Arid et semi-arid lands" (ASALs) of Kenya. More significantly, these factors lead to recurrent food shortage in Machakos District of Kenya. This has been attributed to both endogenous and exogenous factors pertaining to on-farm management and environmental changes, respectively. This study used hydro-geomorphologic risk assessment, social impact and economic inventory models to evaluate farmers' water use efficiency. This procedure referred to as "hydro-economic inventory" assesses the risks related to the use of water and land in farming, and its impact on the social welfare of farmers and the economic viability of their activities. It serves as a basis to the planning, monitoring and evaluation of water disasters in agriculture in that catchment area. It focuses on an incremental analysis of crop water requirements and farmers' water demand under fluctuating rainfall regimes using hybrid inventory models. Results of this study show that significant increase of water shortage costs under below normal rainfall regime (BNOR) undermines agricultural efficiency. Almost all farming units need to define a "Minimum efficient scale" (MES) of their farming water demand to optimize their crop water requirements under recurrent risk of drought. Farmers also need appropriate farming technologies and rational water policies to foster their economic efficiency.

***Keywords:*** *hydro-economic inventory, crop water requirement, climate change, farming water optimization.*



## INTRODUCTION

Since Euler's resource optimization theory of the $18^{th}$ century, scientists are still in search of efficient methods of water allocation and rational use to improve the production efficiency (Clarke and King, 2004; Mccormick and Powell, 2004; Swarp et al., 2007; Sehring, 2008). In marginal and dry lands of Kenya, water scarcity and its unsustainable use are propounded to be the primary cause of agriculture inefficiency, food insecurity and poverty levels increase (Shisanya, 1996; K'akumu, 2008). There results in increased unit costs per water drop, insufficient crop water use and high risk of crop failures (Lal, 1993; Lòpez-Baldovin et al., 2006). Inventory models are suggested to be major tools for assessing efficiency, effectively forecasting and allocating resources, even under uncertainty (Charnes et al., 1978; Chavas et al., 2005; Oduol et al., 2006; Gabriel et al., 2007). (Fildes et al. ,2008) observe that the increased specialization of these fields has been narrowing the scope of interest of operational research. Yet, the latter remains vigorous in forecasting and planning. To achieve both agriculture and environment sustainability, inventory models may thus be very helpful in integrating spatially distributed variables of plant water with mathematical description of water availability and farmers' water demand (Brasington et al., 1998; Efkih et al., 2009).

This study evaluated farmers' water demand using inventory models under the scenarios of above normal (ANOR), normal (NOR) and below normal (BNOR) rainfall regimes. Specifically, it sought to rationalize and optimize crop water requirement and crop yield in terms of farming water economic order quantity (EOQ) under the above three scenarios, in terms of absolute EOQ, an EOQ that fits a limit average cost (LAC), and the one that corresponds to the minimum efficient scale (MES), respectively.

## MATERIALS AND METHODS

This section presents the research methodology and modelling approaches applied in watershed planning and evaluation.

### *Data Collection and Analysis*

Data for this study were collected using questionnaires administered to 66 farms randomly selected in Muooni dam site Other data were collected through in-depth interviews involving 60 civil servants and professionals working in Muooni catchment. This catchment has a small area of 25 $km^2$ situated in Mitaboni location of Kathiani Division in Machakos District in Eastern Province of Kenya (Figure 1). Located in the upper midland agro-ecological zone 4 (sunflower and maize zone), its climatic conditions range from humid to arid. The study used a stratified random sampling of farms located in the dam site. Three different categories of smallholder farms were considered, namely: large scale farms (LSF), medium scale farms (MSF) and small scale farms (SSF). LSFs had more than 2.5 acres of land each, with a minimum of Kenya Shillings (KES) 288,000 annual income. MSFs farmland was between 1 to 2.5 acres, yielding about KES 72,000 to 288,000 each year. SSFs had less than 1 acre of land, and a maximum of KES 72,000 annual income. To assess water stress related food shortage facing farmers, the study applied inventory models to simulate farmers' water demand under the hypothesis of rainfall fluctuation.

### *Inventory Modelling Approaches Applied in Watershed Planning and Evaluation*

### *Modelling Hypotheses*

This study used hybrid inventory models to achieve its objectives. These models were adapted after Wilson inventory model, Baumol monetary model and Beranek treasury model (Luwesi, 1999; Swarp *et al.,* 2007; Fildes *et al.,* 2008). They helped in computing farmers' water EOQ, LAC and MES quantities. The analysis assumed that soil and water losses reduce agricultural efficiency through increased costs of production. If the total farming water cost under NOR rainfall regime is a combination of respective costs of transaction ($C_t$ ) and opportunity costs ($C_o$), it is likely to be loaded by the costs of water saving ($C_s$) under above normal (ANOR) rainfal regime, and by water shortage costs ($C_s^*$) under below normal (BNOR) rainfall regime.

The study assimilated rainfall fluctuation from changes of Muooni river regime. These are also reflected in the fluctuations variations of the active water storage capacity of its dam (Musy, 2001). Therefore, the NOR scenario in this study refers to an active water storage capacity of the dam that is relatively equal to the median capacity designed by engineers. The ANOR and BNOR scenarios are associated to an active water storage capacity that is above the median, and below the median and/or the threshold, respectively. Under the NOR scenario, it was hypothesized that the farming activity was not resulting in significant profits or losses. Farmers were only bearing normal costs of transaction and opportunity costs. However, under ANOR and BNOR scenarios, the farming activity was to result in significant profits or losses, whenever farming water costs were overloaded or not by important water saving or shortage costs. For assessing farming water use efficiency, the study compared all farming total, average and marginal costs with those of the least efficient farms selected among the LSF, MSF and SSF. These were considered as farms reaching the minimum efficiency threshold. An incremental analysis was done for each farming scale under the three scenarios retained (ANOR, NOR and BNOR).

### *Modelling Measurements*

Crop water requirement ($W_t$) for *t* period of crop growth was derived from "Virtual water values" as:

$$W_t = \Sigma ETP_c \qquad \text{(Formula 1)}$$

Where,

$ETP_c$ is the total evapotranspiration (in $m^3$) for *c* different crop types sown during *t* period of crop growth. This variable was computed using FAO (2008) reference crop evapotranspiration ($ET_m$, in $Kg/m^3$) as:

$$ETP_c = \frac{1}{ET_m} x Y_c \qquad \text{(Formula 2)}$$

Where,

$Y_c$ is the total crop yield (in Kg)

It is worth to note that the FAO (2008) reference crop evapotranspiration expressed in terms of crop yield per cubic meter is not strictly a measure of evapotranspiration but of water use efficiency. Under normal conditions, crop evapotranspiration determine farmers' water demand and is thus considered to be a key variable in assessing efficiency of farming water use. In case of fluctuation of rainfall, farmers' water demand is factored by water availability in the catchment. So, the farmers' operational water demand ($W_f$) is finally calculated as follows:

$W_f =$ $r. W_t$ (Formula 3)
Where,
*r is* the water demand turnover, which is a measure of water availability in the catchment, and theoretically derived from inventory models as :
$r = 2/n =$ (Formula 4)
Where,
*n* is the total number of water withdrawals by the farmer over a certain period of time
Finally, farmers' operational water demand ($W_f$) derived from crop water requirement is computed as follows:
$W_f = 2W_t /n$ (Formula 5)
Where,
$W_t /n$ is the average crop water requirement (for two daily withdrawals by the farmer)
It should be noted that this study derived the operational water demand turnover ($r$) from the ratio of the active water storage capacity of the dam $(\hat{S}_t)$ by its designed median $(S_{mé})$. It was hypothesized that the volume of water contained in the dam was decreasing due to the siltation of its reservoir. Thus, the storage capacity of the latter was no longer the same as designed by engineers. This active storage capacity would be an indicator of water availability in the dam site, especially for irrigation purpose.
All the farmers' income (*Y)* and expenditures (*E)* were standardized as follows:
$Y = P.\ W_t /n.Q$ (Formula 6)
$E = P.\ W_t /n.q$ (Formula 7)
Where,
*Q* was the standardized farming activity output
*q* was the standardized farming activity input
*P* was the standard water price per m$^3$
The total farming water cost function was computed under the NOR scenario as:
$TC_{no} = C_t\ (=n.E) + C_o\ (= r.Y) \ = Y\ r + 2E/\ r$ (Formula 8)
The total farming water cost function under the ANOR scenario was the following:
$TC_{an} = C_t\ (=n.E) + C_s\ (= r.Y + l\prod) = (Y+\prod)r - \prod + 2E/\ r$ (Formula 9)
Where,
$\prod$ was the farmer profit, computed in absolute values of *Y-E*.
*l* was the loss of water profitability under above normal rainfall (equal to *r*-1)
The total farming water cost function computed under the BNOR scenario was:
$TC_{bn} = C_t\ (=n.E) + C^*_s\ (= r.Y + l^*\prod) \quad = (Y-\prod)\ r + \prod + 2E/\ r$ (Formula 10)
Where,
$l^*$ was the loss of water profitability under below normal rainfall (equal to 1-*r*)

The Average Cost (AC) and Marginal Cost (MC) functions were obtained as follows:

$$AC = \frac{TC}{r}$$ (Formula 11)

$$MC = \frac{dTC}{dr}$$ (Formula 12)

From formulas 8, 9, 10 11 and 12, the average and marginal cost functions computed under each rainfall regime scenario were the following ones:
*Under the NOR scenario:*

$$AC_{no} = \frac{TC_{no}}{r_{no}} = Y^2 + 2E/\ r^2$$ (Formula 13)

$$MC_{no} = \frac{dTC_{no}}{dr_{no}} = Y - 2E/\ r^2$$ (Formula 14)

*Under the ANOR scenario*:

$$AC_{an} = \frac{TC_{an}}{r_{an}} = Y + \prod - \prod/\ r + 2E/\ r^2$$ (Formula 15)

$$MC_{an} = \frac{dTC_{an}}{dr_{an}} = Y + \prod - 2E/r^2 \qquad \text{(Formula 16)}$$

*Under the BNOR scenario:*

$$AC_{bn} = \frac{TC_{bn}}{r_{bn}} = Y - \prod + \prod / r + 2E/r^2 \qquad \text{(Formula 17)}$$

$$MC_{bn} = \frac{dTC_{bn}}{dr_{bn}} = Y - \prod - 2E/r^2 \qquad \text{(Formula 18)}$$

Using the operational water demand turnover generated by the variations of the active water storage capacity of the dam, the analysis computed expected costs and water demand values. After optimization of the said water demand turnover, minimum farming water costs (EOQ, LAC and MES) and demand were obtained under ANOR, NOR and BNOR scenarios, for each farming scale. The first order conditions leading to the calculation of EOQ, LAC and MES were as follows:

*Under the NOR scenario:*

$$\bar{r}_{no} = \sqrt{2q/C} \qquad \text{(Formula 19)}$$

*Under ANOR scenario:*

$$\bar{r}_{an} = \sqrt{2q/(C-2e)} \qquad \text{(Formula 20)}$$

*Under BNOR scenario:*

$$\bar{r}_{bn} = \sqrt{2} \qquad \text{(Formula 21)}$$

Using each optimized $r$ values, farmers' water demand ($\bar{W}_f$) at the EOQ, LAC and MES levels were computed under hypotheses of significant profit (ANOR), no significant profit or loss (NOR) and significant loss (BNOR) as follows:

$$\bar{W}_f = \bar{r}\ W_c \qquad \text{(Formula 22)}$$

## RESULTS AND DISCUSSION

This section expands on fieldwork results and their discussion. It includes results and discussion of the ex post socio-economic and environmental impact assessment, of the assessment of farmers' water demand and their crop water requirement, and the optimization of farmers' water demand requirement under fluctuating rainfall regimes.

### *Ex Post Socio-Economic and Environmental Impact Assessment*

Muooni catchment is facing severe environmental issues in addition to coping with high population pressure and over-reliance on water for livelihood, especially for irrigation. Erosional processes, erratic rainfalls, river flows and forests cover depletion; silting drainage systems and degradation of asset investments are making farming activities inefficient. Table 1 shows that deforestation and bad land husbandry are primary causes of Muooni catchment degradation. Due their inadaptability to Muooni catchment's ecosystem, eucalyptus and other alien trees planted in the catchment have more severe impact on its water storage, as they pump more than usual water through evapotranspiration. Other critical factors contributing to this catchment degradation include landslide and gully erosion in farmlands, as well as encroachment of agricultural activities on wetlands, and sheet and/or rill erosion from farms. On-site effects of soil erosion and water over-abstraction by eucalyptus and other alien trees have adverse effects on the modification of the catchment's microclimate, leading to bare, loose and rocky soils. This in turn results on a process of subdivision of farmlands for the purpose of settlement (Luwesi, 2009; Jaetzold et al., 2007). This study showed that these endogenous on-farm management factors are highly correlated to farmers' education and poverty. Yet, there are other factors related to rainfall fluctuation that impact on the catchment degradation; these are El Niño floods and droughts, high wind pressure and other changing climatic patterns. They increase the risk of loss of soil fertility under water stress through off-site effects of global warming and high wind pressure. Figure 2 shows that Muooni dam's water storage capacity is decreasing at an annual rate of 6.2 %, likely because of sediment loads into the dam reservoir and its water resource over-abstraction. It is expected to be under its threshold by the year 2019, storing about 119,287.4 $m^3$ of Muooni River streamflow. This descent really justifies water stress facing farmers in Muooni catchment. If no urgent action is taken, water scarcity will result in significant costs of water transaction, water shortage and opportunity costs as well as socio-economic externalities threatening food security, agriculture viability and community livelihood in the catchment.

***Assessment of Farmers' Water Demand and their Crop Water Requirement***

Table 2 gives an idea of farmers' physical income and costs (in Kenya Shillings currency, in short KES) for each farming scale. It shows that all farmers' categories (LSF, MSF and SSF) are incurring losses. This implies that farmers mainly optimize their faming water costs to ensure high yields and incomes. Thus, to determine the optimum of farmers' water demand, the analysis first computed the actual crop water requirement. Then, it simulated farmers' water demand from their operational costs and an operational water demand turnover. The water demand turnover computed under ANOR ($r_{an}$=1.0435), NOR ($r_{no}$=0.6169) and BNOR ($r_{bn}$=0.1319) scenarios represented the ratio of the active water storage capacity of Muooni dam estimated for the years 1988, 1998 and 2020, by the designed median storage capacity of 836,000 $m^3$. Farming water cost functions were computed from daily observed operational costs of the least efficient farms selected among each farming category (LSF, MSF and SSF). The total cost functions below were obtained under each rainfall regime scenario:

***Under ANOR scenario:***

$LSF\ TC_{an} = 800.83\ r + 99.17 + 1{,}998.34/r$ (Formula 24)

$MSF\ TC_{an} = 751.94\ r + 8.06 + 1{,}536.12/r$ (Formula 25)

$SSF\ TC_{an} = 133{,}53\ r + 21{,}47 + 352.94/r$ (Formula 26)

***Under NOR scenario:***

$LSF\ TC_{no} = 900\ r + 1{,}998.34/r$ (Formula 27)

$MSF\ TC_{no} = 760\ r + 1{,}536.12/r$ (Formula 28)

$SSF\ TC_{no} = 155\ r + 352.94/r$ (Formula 29)

***Under BNOR scenario:***

$LSF\ TC_{bn} = 999.17r - 99.17 + 1{,}998.34/r$ (Formula 30)

$MSF\ TC_{bn} = 768.06\ r - 8.06 + 1{,}536.12/r$ (Formula 31)

$SSF\ TC_{bn} = 176.47\ r - 21.47 + 352.94/r$ (Formula 32)

Results show that rainfall fluctuation really threatens the economic viability of farming activities at Muooni catchment. Water stress is the principal factor limiting the agricultural efficiency and fostering food shortage in Muooni catchment. Farmers' water demand is generally not enough to meet their crop water requirements. Table 3 reveals that there is a gap of 71.15%, 87.8% and 95.57% between water demand and crop water requirement of LSF, MSF and SSF, respectively. The small share of water demand by farmers is explained by increased costs of rainwater saving and water shortage costs under ANOR and BNOR, respectively. Under ANOR, farmers' water demand decrease is explained by high soil moisture and fields destruction by water erosion and flooding. Likewise, perennial loss of land fertility and water stress due to drought result in crop failures and loss of yields under BNOR. Yet, even under normal conditions, farmers do not order sufficient water for their crops, the differential being filled up by soil moisture and/or illegal water abstraction from the dam. Table 4 suggests that farmers' water demand decreases more significantly under BNOR due to excessive costs of dam's water shortage boosting the cubic meter to more than 1,140% of its actual price. This can be illustrated by the variations of water prices from KES 5 to 60 per 20 litres-jerrycan during the 2009 drought in Kathiani division. Farmers lost most of their crop yields and cattle due to lack of water. Consequently, most farmers have adopted a strategic farming method for facing poor yields and incomes, especially during unpredictable droughts. It consists of using excessive intercropping and multiple cropping of perennial indigenous and alien crop species on small farmlands. Yet, this cannot limit significantly their operational costs and losses. Water over-abstraction by eucalyptus and other alien trees along with off-site effects of El Niño flooding and drought accelerate the risk of soil erosion and water excess loss. With a declining rate of farming area of 40% in about 10 years, excessive intercropping and multiple cropping result in a "land harassment". This strategy later rebounds on the dam's active water storage capacity by spoiling its water reserves and loading important sediments in the dam's reservoir, especially (after tree harvesting). This negative evolution of the active water storage capacity of the dam affects considerably the quantity and price of water in the catchment, resulting in high costs of agricultural production. (Jaetzold et al ., 2007) conclude: "it is this mismatch of crops against the suitability of the agro-ecological zone that contributes to persistent crop failures in these areas".

***Optimization of Crop water requirements under Fluctuating Rainfall Regimes***

It is imperative that farmers optimize their crop water requirement under the limits of affordable costs and efficient production. To optimize operational farming water costs, the study conducted an incremental analysis. Optimum water demand turnover values were computed from marginal operational cost functions, under ANOR, NOR and BNOR rainfall scenarios. Results from Figure 3 revealed that farmers needed to match their water orders with their “economic order quantity” (EOQ), if their actual crop water requirements were to be met. Under ANOR, the EOQ was absolutely profitable to all the farmers. However, it corresponded to their “limit average costs” (LAC) and “minimum efficient scales” (MES) under NOR and BNOR, respectively. The required farming water quantity was to be slightly above the current crop water requirements to avoid any shortage under unexpected drought. Daily water demands of the least efficient farms selected were 13.86 $m^3$ (for LSF), 11.57 $m^3$ (for MSF) and 3 $m^3$ (for SSF), respectively. Under ANOR, these farmers rationally needed to order a quantity corresponding to the EOQ of 21.9 $m^3$, 16.54 $m^3$ and 4.88 $m^3$, respectively. Under NOR, they needed 20.66 $m^3$, 16.45 $m^3$ and 4.53 $m^3$ of water to match their respective LAC. Quantities fitting their respective MES were 19.61 $m^3$, 16.36 $m^3$ and 4.25 $m^3$ under BNOR. A decision on water demand to meet an EOQ, a LAC or a MES was not only to be based on the physical rainfall regime, but more likely on the economic profitability of farming activity.

These results attested that farming profitability under ANOR was the most important economic incentive that led to the process of farmlands subdivision, eventually from 1987 to 2003, due to high water productivity in the catchment. Figures from Table 3 and Table 4 show that the unit cost per $m^3$ of water was established at KES 197, 187.5 and 159.2 for LSF, MSF and SSF, respectively. Yet, new farmers entering the agricultural industry had less absolute cost advantages than existing farmers. Their average costs being significantly higher than the latter in the short-term, they had to adopt respective limit average costs (LAC) of KES 443.7, 414.5 and 360.3 (for LSF, MSF and SSF), if any loss was to be avoided. Cost advantages of existing farmers might have included technological advantages, farming skills and knowledge of the environment as well as other factors helping them to minimize external costs. Finally, satisfactory credit ratings and patents allowing them to purchase inputs and borrow money at lower rates might have been among such advantages attracting new entrants (Nicholson, 1992). To improve their cost advantages, new entrants needed a lot of time to develop specific on-farm management skills and credentials. Though they had less absolute cost advantages than their competitors, they were hoping to improve their competitiveness in the medium-term or long-term. However, things turned around with high degradation of the catchment and increased ‘low fertile soils and unfavourable climate’ (Jaetzold et al., 2007). To improve their poor yields and incomes, some attempted in vain to practice mass production by ordering water levels that meet the above EOQ or LAC. This might have obliged them to sacrifice their short-term benefits by adopting a MES of KES 830.3, 769.2 and 676 for LSF, MSF and SSF, respectively. In some cases, farmers simply abandoned their farming activities by adopting off-fam activities such as jobs in public and private sectors, small scale businesses (Luwesi, 2009).

A comparison between the MES average costs and the expected farming income established that farming activities are no longer effective in Muooni catchment (Table 5). Efficacy necessitates that farmers enhance their actual water productivity at least by 76 % under any rainfall regime to increase their crop yields. Smallholder farms need to increase their water demand at the MES level to meet their crops water requirements. Thus, they would be able to limit their losses and expect further increased income through high yields under any rainfall regime. Therefore, farmers need to implement rational water use methods in farming. This means they should adopt efficient crop selection and specialization (to 2 or 3 crops). They also need appropriate alternative technologies that value allocative efficiency of agricultural water resources and foster farming technological efficiency within the production possibility frontier (Ellis, 1993; GoK, 2007). Besides, farmers need to monitor regularly their water demand from the dam to adjust accordingly their crop water requirements. They are also encouraged to make farming joint ventures, purchase green water credits and import virtual water under the leadership of a “water resource users’ association” (WRUA) and the management of the “water resource management authority” (WRMA). The latter is suggested to adopt new mechanisms of water allocation by instituting water use permits, meters, fees and charges (GoK, 2002; Foote et al., 2007; K’akumu, 2008). The introduction of water fees and charges in Muooni catchment may foster higher profits if farmers are able to calculate in advance their margin profit and choose adequate crop type and method of production (Förch et al., 2008). Thus, they may hinder water conflicts through equitable water distribution and fair share of the resource, especially under stress and scarcity.

***Statement of Contribution***

Most applied irrigation models are based on agro-ecological variables of plant water evapo-transpiration, while water pricing and income are keys for irrigation water supply. Planning irrigation efficiency needs to integrate both farmers’ economic power and agro-ecological variables of their farming production, especially under uncertain conditions of water availability. Hydro-economic inventory (HEI) is a step toward “Integrated watershed management” (IWM). It is a major goal towards sustainable management of water and related resources. It is especially designed to improve irrigation planning in the course of climate change within various agro-ecological zones. In effect, HEI establishes a link between the physical factors determining farmers’ optimal production and the market processes determining its efficiency under three scenarios of farming water fluctuations: Above Normal (ANOR), Normal (NOR) and Below Normal (BNOR) rainfall regimes. Using hybrid inventory models it optimizes the water demand turnover from the farming water total cost function to determine the “Economic order quantity” (EOQ) under ANOR, the “Limit average cost” (LAC) under NOR, and the “Minimum efficient scale" (MES) under the BNOR. This paper presents the mathematical modelling of these three indicators of farming water efficiency.

## CONCULSION

Food shortage in Muooni catchment is a result of both endogenous on-farm management factors and exogenous environmental agents that enhance the rate of fertile soil loss and of water stress. On-farm land management is highly correlated to farmers' education and economic poverty, while off-site effects of El Niño floods and droughts are more related to rainfall fluctuation. All these factors increase significantly the total farming water cost through high costs of water transaction, water saving, shortage and opportunity costs. For efficiency, farmers need to define their crop water requirements to a level that fits an absolute economic order quantity (EOQ), or a limit average cost (LAC) or finally a minimum efficient scale (MES), under above normal, normal and below normal rainfall regimes, respectively. They need thus to implement rational farming water use methods, notably crop selection and specialization (to 2 or 3 crops) and appropriate farming technologies that foster allocative and technological efficiency within the production possibility frontier. Finally, they also may opt for farming joint ventures, purchase green water credits and import virtual water to enhance efficiency. WRMA should therefore speed up the implementation of water sector reforms by metering and charging water consumption through development of a catchment management strategy (CMS) in the Athi catchment in general, and Muooni sub-catchment in particular. This may be a sustainable remedy to water stress and crop failures as well as to farmers' poverty in the catchment.

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