Distribution Pressure Management based on Hydraulic Model for Intermittent Supply

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Abstract

To overcome problems of high leakage rates and inequitable water supply under intermittent supply, we propose a new distribution pressure management technique based on a hydraulic model for intermittent supply. Tank system models are used to simulate pressure-driven demand, which is characteristic of intermittent supply. The hydraulic model for intermittent supply is constructed by incorporating the tank system models into a common hydraulic model. In the proposed pressure management technique, two indicators (the supply satisfaction rate and leakage rate for various pressures of water discharged into a distribution network) are calculated on the basis of the hydraulic model for intermittent supply to help operators decide to the appropriate discharged pressure. Results of a simulation study using a virtual network model showed that the trade-off graph of the two indicators and the supply satisfaction level of each consumer node can be visualised and used for decision making. They also showed that the technique contributes to equitably supplying water among sub-zones and reducing leakage for supply zones.

Keywords: Pressure management; Intermittent supply; Hydraulic model; Pressure-driven demand

Introduction

The level of suppliable water in some developing countries is often much lower than water demand due to high leakage rates and rapid economic growth. To limit water supply, intermittent supply is commonly used where supply is limited to 1-2 or 3-4 hours per day, or where water may be supplied only every two days.

In the areas with intermittent water supply, each consumer has a household tank to accumulate water for daily use. Since the amount of water provided during intermittent supply is not enough, consumers are forced to accumulate as much water as possible during those short hours. In this process, the flow control valve attached to the household tank system is kept fully open. This causes pressure-driven demand, which means that high pressure produces high demand. In these circumstances, consumers with high supply pressure receive more water than consumers with low supply pressure.

To reduce water leakage and energy consumption, numerous pump operation scheduling and distribution pressure control techniques have been proposed. Almost all techniques target continuous water supply systems, not intermittent ones (Gao et al. 2014; Roshani and Filion 2014; Bohorquez et al. 2015; Odan et al. 2015). Transmission water flow control based on an inversion-based controller was proposed to equitably supply water to each distribution zone (Manohar and Kumar 2014). Moreover, to simulate pressure-driven demand, techniques without source code modification of EPANET have been proposed. They are based on inserting components including a check valve, flow control valve, emitter, and so on in series to demand nodes in the EPANET model (Muranho et al. 2014; Abdy et al. 2014; Pacchin et al. 2017). The other technique used a roof tank model to express pressure-driven demand (Ingeduld et al. 2008).

To overcome problems of high leakage rates and inequitable water supply, we propose a new distribution pressure management technique based on a hydraulic model for intermittent supply. Tank system models are used to simulate pressure-driven demand under intermittent supply. The hydraulic model for intermittent supply is constructed by incorporating the tank system models into a common hydraulic model. Tank system models are structured by integrating the actual household tanks in the same manner in which demand of a consumer node in a hydraulic model is structured by integrating the demand of several actual consumers. For accurate simulation, fair values of parameters of the tank system models were determined by physical considerations. For example, the diameter of the service pipe connecting the tank to the distribution pipe was determined using the Hazen-Williams formula, so that the head loss in the tank system models is equal to that in the actual tank systems.

In the proposed pressure management technique, two indicators (the supply satisfaction rate and leakage rate for various pressures of water discharged into a distribution network) are calculated on the basis of the above mentioned hydraulic model for intermittent supply. The former indicator is novel and is defined as the ratio of total water supply to all consumer tanks in a day to its target value. These indicators are for the entire network and have a trade-off relationship. High pressure creates high supply satisfaction but also brings about an undesirable high leakage rate. One solution is to use discharged pressure to achieve a supply satisfaction rate of around 100%. An operator can decide the appropriate discharged pressure by considering the trade-off of the two indicators. Moreover, by checking if the water level of each tank at the end time of the hydraulic simulation is over the initial level or not, the operator can determine the supply satisfaction level of each consumer node. This technique can also be applied to a network with supply rotation in which the entire network is divided into several sub-zones and water supply is rotated among them. By providing different discharged pressure to each sub-zone, water can be equitably supplied among sub-zones.

The above mentioned pressure management technique is applied to a water distribution network, and four cases where supply is intermittent or continuous, supply time is 4, 6, or 24 hours a day, and supply is or is not rotated are evaluated by simulation.

Methodology

Hydraulic Model for Intermittent Supply

To simulate pressure-driven demand under intermittent supply, a tank system model was incorporated into a common hydraulic model. As shown in **Fig. 1**, actual tank systems were approximated as a tank system model with one service pipe, one tank, and one household. Fair values of parameters in the tank system model were determined by three physical considerations.

1) Sectional area of a tank system model is the sum of real sectional area (S=nxS1)
2) Demand of a tank system model is the sum of real demand (Q=nxQ1)
3) Service pipe diameter of a tank system model is derived on the basis of the formula of Hazen Williams.

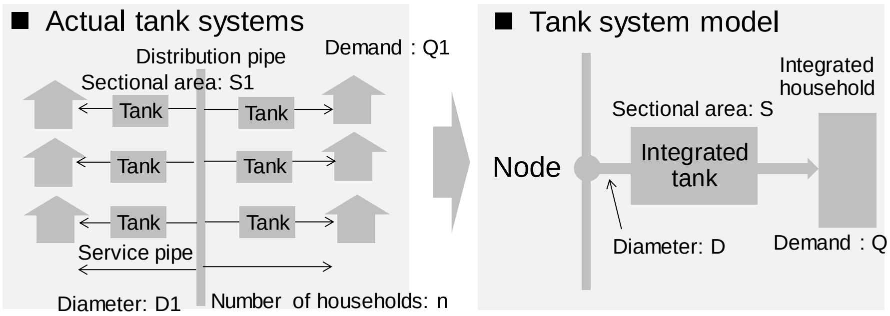


Figure 1 Tank system model

By applying the formula of Hazen Williams to actual systems and a tank system model, the following equation is derived. Here, the same head loss was assumed in the actual system and the model.

$$\Delta P = k\frac{Q_1^{1.85} \cdot L}{C^{1.85} \cdot D_1^{4.87}} = k\frac{Q^{1.85} \cdot L}{C^{1.85} \cdot D^{4.87}}$$

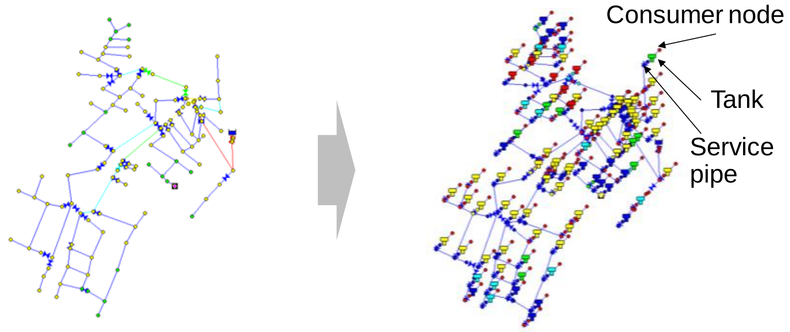
where Q_1 is the flow rate in the actual system; Q is the flow rate in the model; D_1 is the diameter of the service pipe in the actual system; D is the diameter of the service pipe in the model; C is the pipe roughness; and L is the length of the service pipe.

By solving the equation for parameter D, the following equation is derived.

$$D = D_1 \cdot \left(\frac{Q}{Q_1}\right)^{\frac{1.85}{4.87}} = D_1 \cdot \left(\frac{Q}{Q_1}\right)^{0.380} = D_1 \cdot n^{0.380}$$

For example, D=57 mm when D_1=13 mm and n=50.

As shown in **Fig. 2**, the hydraulic model for intermittent supply (EPANET inp file) is created from an original model by a conversion program. Service pipes, tanks, and consumer nodes are newly added. The demand pattern with demand peaks in the morning and the evening was assumed at the consumer node.



(a) Original model

(b) Model for intermittent supply

Figure 2 Creation of hydraulic model for intermittent supply by conversion program

Distribution Pressure Management

Two indicators (supply satisfaction rate and leakage rate for various pressures of water discharged into a distribution network) are calculated on the basis of the above mentioned hydraulic model. The supply satisfaction rate is defined as the ratio of total water supply to all consumer tanks in a day to its target value. For example, the target value is calculated as the product of target demand per capita and the number of consumers. An example of the calculation result is shown in **Fig. 3**. The two indicators have a trade-off relationship. High pressure creates high supply satisfaction but also brings about an undesirable high leakage rate. One recommended solution is to use discharged pressure at a supply satisfaction rate of 100%.

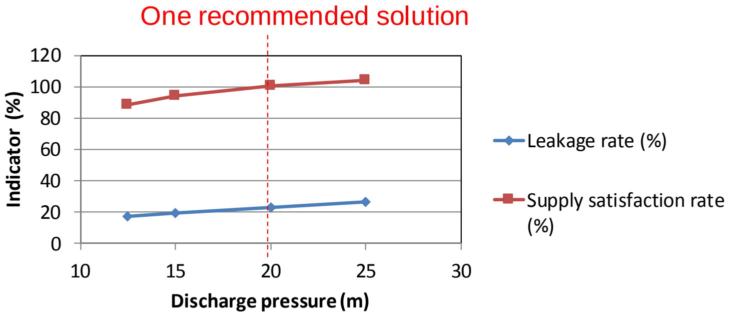


Figure 3 Calculation example of two indicators

Case Study

Simulation Model and Condition

The virtual network shown in **Fig. 4** was used for a case study. The area is about 3 × 3 km. Daily total demand is about 10,000 cubic meters. Terrain in the residential area is mostly flat, and the reservoir is located 60 m higher. Supply time is four or six hours a day. Tank height is 1 m. Initial tank water level is 0.8 m. To control the water level, a control valve is opened and closed at water levels of 0.98 and 1.02 m, respectively. Discharged pressure is controlled by using a pressure release valve (PRV).

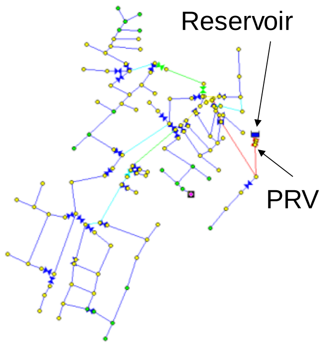


Figure 4 Water distribution network model used in case study

Simulation Results

The proposed pressure management technique was applied to four cases in **Table 1** and evaluated in simulations. Water supply is intermittent in cases 1, 2 and 3 and continuous in case 4. Supply time is six hours in case 1 and four hours in cases 2 and 3. Only case 3 has supply rotation among three zones. The levels of leakage, inequitable supply, and energy consumption were compared among the four cases.

Table 1 Four cases of simulation study

Case	Supply type	Supply time (hours/day)	Supply rotation
1	Intermittent	6 hours	No
2	Intermittent	4 hours	No
3	Intermittent	4 hours	Yes (3 zones)
4	Continuous (24/7)	24 hours	-

(1) Case 1

Time periods of water supply are 6:00 - 9:00 and 17:00 – 20:00. Two indicators were calculated on the basis of hydraulic simulation (**Fig. 5**). The supply satisfaction rate is about 100 % at a discharged pressure of 20 m. In this condition, the leakage rate is 22.9%. Under a discharged pressure of 20 m, tank water levels at 24:00 were calculated (**Fig. 6**). The tank colour indicates the tank water level with red as the highest and navy as the lowest. Consumers with yellow tanks are satisfied with the daily water supply because the tank water level at 24:00 is larger than the initial water level of 0.8 m. **Fig. 6** shows that water supply is insufficient for consumers at end nodes. The problem of inequitable supply exists in the overall network.

(2) Case 2

Time periods of water supply are 6:00 – 8:00 and 18:00 – 20:00. The calculation results of two indicators are shown in **Fig. 7**. The supply satisfaction rate is about 100 % at a discharged pressure of 45 m. In this condition, the leakage rate is 29.2%. The results showed shorter supply time needs higher pressure and increases the leakage rate. Tank water levels at 24:00 were calculated on the basis of a hydraulic simulation (**Fig. 8**). Consumers with yellow tanks are satisfied with the daily water supply. Water supply is insufficient for consumers at end nodes as in case 1. There are more unsatisfied consumers than in case 1. A supply time of six hours may be preferable because the leakage rate is lower and the number of satisfied consumers is larger.

(3) Case 3

The overall network was divided into three zones, and water supply was rotated among them. As shown in **Fig. 9**, the rotation order is Zone 3, Zone 2, and Zone 1. Supply rotation is expected to contribute to equitably supplying water among the sub-zones. **Table 2** compares the calculated leakage rates and supply satisfaction rates in cases 1, 2, and 3. Water was equitably supplied among three zones by setting pressure of zones 1, 2, and 3 at 40, 30, and 15 m, respectively. However, case 3 has a higher leakage rate than case 1 with a supply time of 6 hours. **Fig. 10** shows tank water levels at 24:00. In case 3, the problem of inequity among zones has been solved, but the problem of inequity within zones remains.

(4) Case 4

As shown in **Table 3**, under continuous supply, a supply satisfaction rate of about 100 % is maintained regardless of the discharged pressure. However, the leakage rate jumps because leaks occur over 24 hours. Moreover, the energy consumption index that corresponds to actual energy consumption was calculated assuming use of booster pumps. The index is given as the product of discharged pressure and total water supply to the network.

$$\text{Energy consumption index} = \sum_{i=0}^{24} P(t)Q(t)$$

where P is the discharged pressure (m), Q is the total supply to the network (l/s), and t is the time.

The simulation results showed the energy consumption in continuous supply is lower than that in intermittent supply under low discharged pressure because discharged pressure is lowest in case 4. **Fig. 11** shows tank water levels at 24:00 for discharged pressures of 7.5 and 10 m. The results showed continuous supply can solve the problem of inequitable supply to each consumer because most tanks are kept full even though the leakage rate increases.

Summary

Supply rotation contributes to equitably supplying water among sub-zones although the problem of inequity among consumers remains. If intermittent supply without rotation achieves a low leakage rate, it may be one solution that we should adopt. The leakage rate must be reduced sufficiently before transition to 24/7 supply because continuous supply may create more leakage.

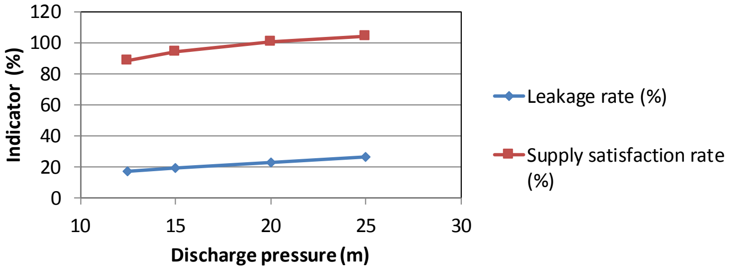


Figure 5 Two indicators in case 1

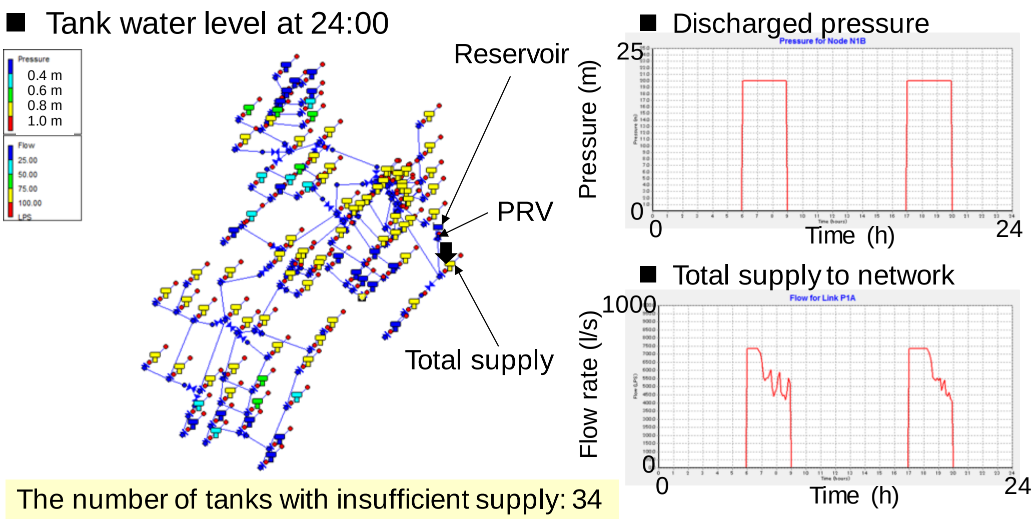


Figure 6 Tank water level at 24:00 in case 1

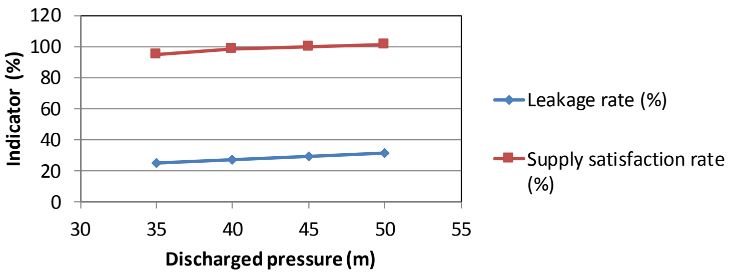


Figure 7 Two indicators in case 2

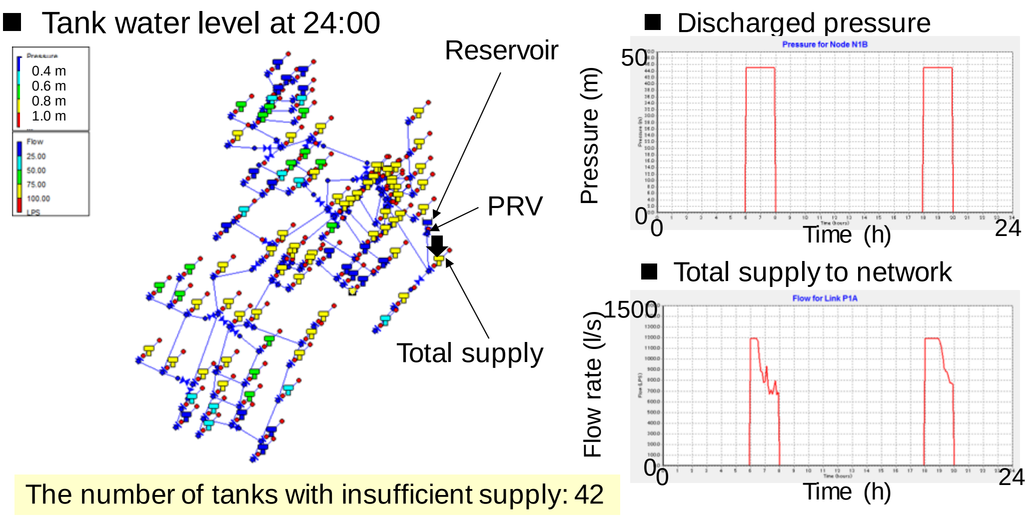


Figure 8 Tank water level at 24:00 in case 2

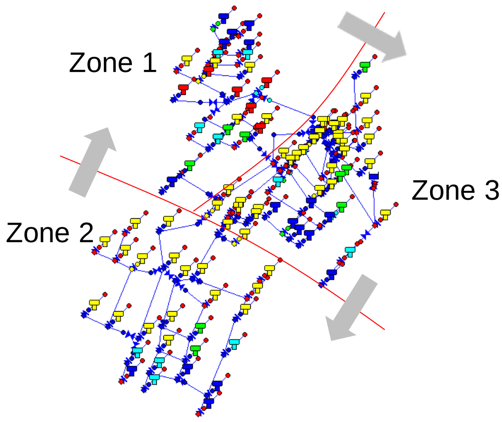


Figure 9 Supply rotation in case 3

Table 2 Leakage rate and supply satisfaction rate in case 3

	CASE 1	CASE 2	CASE 3
Supply time (hours/day)	6	4	4
Rotation	No	No	Yes
Discharged pressure (m)	20	45	40 30 15
Leakage rate (%)	22.9	29.2	25
Supply satisfaction rate (%) (Overall zone)	100.8	99.7	100.6
SSR for Zone 1 (%)	87.9	85.6	98.5
SSR for Zone 2 (%)	94.9	92.2	99.9
SSR for Zone 3 (%)	111.6	112.2	102.2

SSR: Supply Satisfaction Rate

Inequity among 3 zones

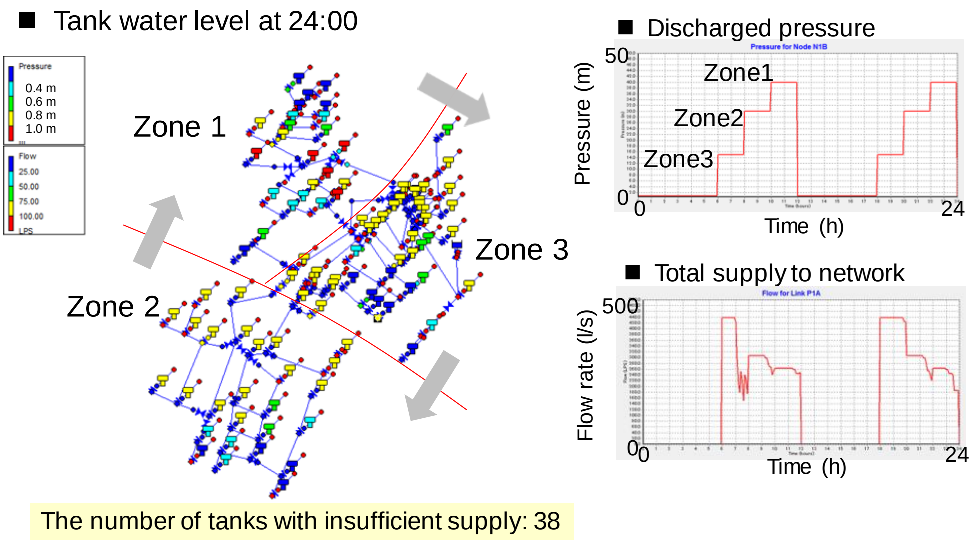


Figure 10 Tank water level at 24:00 in case 3

Table 3 Leakage rate and supply satisfaction rate in case 4

	CASE 4			CASE 1
Supply type	Continuous			Intermittent
Supply time (hours/day)	24			6
Discharged pressure (m)	7.5	10	15	20
Leakage rate (%)	45.6	53.2	62.3	22.9
Supply satisfaction rate (%) (Overall zone)	98.2	98.6	99.5	100.8
SSR for Zone 1 (%)	97.3	99.8	99.3	87.9
SSR for Zone 2 (%)	98.6	98.7	98.6	94.9
SSR for Zone 3 (%)	98.4	97.8	100	111.6
Energy consumption index	3.8×10^5	5.9×10^5	11.2×10^5	7.3×10^5

SSR: Supply Satisfaction Rate

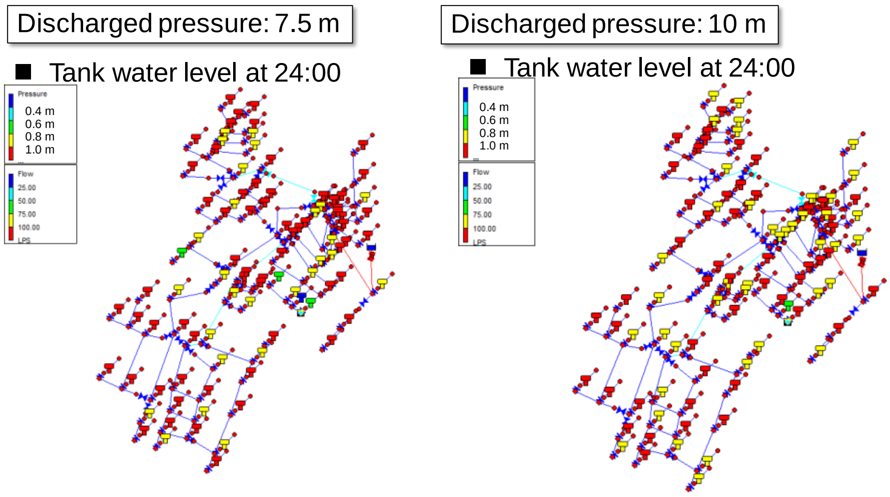


Figure 11 Tank water level at 24:00 in case 4

Conclusion

A new distribution pressure management technique based on a hydraulic model for intermittent supply was proposed. The technique helps operators to decide discharged pressure by using two indicators: supply satisfaction rate and leakage rate. Simulation using a virtual network model showed that the trade-off graph of the two indicators and the supply satisfaction level of each consumer node can be visualised and used for decision making. It also showed that the technique contributes to equitably supplying water among sub-zones and reducing leakage for supply zones.

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