A flow balance approach to scenarios for water reclamation

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Abstract

Water reclamation, or the direct use of treated sewage effluent to replace a proportion of the fresh water demand, is a non-conventional approach to water demand management which is gathering momentum internationally. A recent WRC study showed that the proportion of water reclaimed as a percentage of total wastewater produced in a country ranges from less than 1% for Japan as a whole, to 84% for Israel. However, the same study showed that in South Africa, total direct reclamation of water is estimated to be less than 3% of the total flow of treated sewage effluent discharged to surface and marine waters, estimated to be 1 086 x 10^6 m3/a in 1996.

This paper argues that increasing demand for water caused by urbanisation and industrialisation should be matched by water reclamation, which provides an increasing intensity of land-based treatment and recycle depending on the proportion of total water demand which is satisfied by reclaimed water. The flow balance approach allows for the calculation of the total water availability to the urban reticulation network, following the implementation of water reclamation. Water losses from the system through leakage, evaporation, or use of water for irrigation, must be known. Scenarios for zero effluent discharge to surface waters are explored. In addition to flow balances, salt balances for certain scenarios are given.

Introduction

South Africa is a semi-arid country with limited water resources and a rapidly growing population. With increasing industrial and urban development, the demand on the country's water resources is nearing the point where conventional supplies will soon be exceeded. Planning for the water needs of the country in the future is a complex task, and non-conventional areas must now be addressed to supplement the two major areas of water resource management and water demand management. Water reclamation, or the direct use of treated sewage effluent to replace a proportion of the fresh-water demand, is such a non-conventional approach. Internationally, especially in countries which have water shortages similar to that in South Africa, water reclamation is becoming increasingly common, as shown in a recent Water Research Commission study (Grobicki and Cohen, 1998). However, the study showed that less than 3% of available treated sewage effluent is directly reclaimed in South Africa.

In this paper, "water reclamation" is used as the generic term for the various practices and applications of reusing or recycling treated sewage effluent, industrial effluent, or wastewaters, although the words are used interchangeably. The term water reclamation is preferred for a number of reasons: it is increasingly the accepted term used in the international literature (Crook and Surampalli, 1996; Maeda et al., 1996; Mills and Asano, 1996); it carries a positive environmental connotation; and it avoids the negative social connotations that the terms "wastewater reuse" or "reuse of treated sewage effluent" carry for many people.

Potential applications for the direct reuse of reclaimed water include:

- Construction applications (dust control, soil settling and compaction, aggregate washing, concrete making)
- Domestic - non-potable applications (fire fighting, car washing, toilet flushing, garden watering)
- Industrial applications (cooling towers, boiler feed, quenching, washdown)
- Groundwater recharge (recharge of aquifers)
- Agricultural irrigation
- Provision of potable water (drinking water, either supplied directly or blended with raw water).

The recent study carried out for the Water Research Commission focused primarily upon water reclamation for industrial and other urban applications, rather than on agricultural applications or upon full reclamation to potable water standards. The potential for agricultural applications of water reclamation in South Africa deserves a separate study in its own right. Treatment to potable standard is unnecessarily costly, compared to treatment for direct reuse in non-potable applications. In conventional water treatment and reticulation networks, all water is treated to potable standard, although only a small fraction of water is actually used for drinking. Rather than bringing treated sewage effluent to supplement South Africa's raw water supplies through treatment to potable water standard, this paper argues that substantial treatment cost savings, as well as raw water savings, can be made by short-circuiting this treatment loop and reclaiming water directly for certain uses.

National and international usage of reclaimed water

No overall figures have been found to exist for volumes of water currently reclaimed over the whole of South Africa, nor indeed within individual local authorities (Grobicki and Cohen, 1998). Table 1 shows the major applications in South Africa, which are (in order of importance) : direct reuse in the paper industry, cooling in municipal power stations, and aquifer storage and recharge. Return to rivers (also termed planned indirect reuse in South Africa) is excluded from these calculations of direct reuse and is dealt with in more detail below. Although reclamation for potable purposes is well known and has been practised in Windhoek, Namibia, for over 30 years (Haarhoff and Van der Merwe (1996)), a pilot project at Faure in Cape Town found this application to be financially

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unviable under South African conditions. In 1991, the cost of the fully treated reclaimed water was calculated to be four times that of drinking water (Pieterse and Kfir, 1991). This application is not currently being practised in South Africa.

Figures for other applications, such as the direct use of reclaimed water for urban irrigation, and for various industrial uses, are not currently available on a national basis, although individual wastewater treatment works may be able to supply such figures in certain places. Based on more detailed regional data gathered, total current reclamation of water nationwide is estimated to be less than 30 x 10^6 m^3/a (excluding return to rivers).

TABLE 1
RECLAIMED WATER USAGE IN SOUTH AFRICA
(FROM GROBICKI AND COHEN, 1998)

Application	m^3/a
Aquifer storage and recharge (Atlantis)	2 x 10^6
Industrial water (paper industry)	9.6 x 10^6
Industrial water (other)	Data not available
Cooling in municipal power stations	4.2 x 10^6
Irrigation in urban areas	Data not available

Again, no data are currently available of the total production of treated sewage effluent (TSE) in South Africa. Major point discharges are estimated to be approximately 321x10^6 m^3/a to the oceans, while 715 x10^6 m^3/a is returned into inland rivers and dams. The estimated flow from major point sources therefore totals 1 036 x10^6 m^3/a (DWAF, 1997), but this estimate excludes return flows from small effluent treatment works.

For purposes of comparison, the total production of treated sewage effluent (TSE) in South Africa may be estimated by using a ratio of return of TSE to water demand of 0.5. This ratio is the average of the typical return ratios from a large city (0.65) and a small town (0.35) (Grobicki and Cohen, 1998). Total annual domestic and urban water demand in South Africa was 2 171 x 10^6 m^3/a in 1996 (DWAF, 1997). Hence TSE production in South Africa may be conservatively estimated at 1 086 x 10^6 m^3/a, or 2 975 Mℓ/d. Using a higher return ratio would clearly result in a higher figure for available TSE. Factors which affect the average return ratio for the country as a whole include:

- Use of septic tanks and soakaways
- Leakage in both water pipes and sewerage lines
- Infiltration into sewerage lines
- Regional and seasonal variations in the amount of water used
- The nature of industrial users.

TABLE 2
RECLAIMED WATER USAGE IN VARIOUS COUNTRIES (FROM GROBICKI AND COHEN, 1998)

Place	Year	Wastewater produced (x10^6 m^3/a)	Reclaimed water used (x10^6 m^3/a)	Application
California	1970[#]	Not reported	216	Primarily irrigation
	1987[#]	Not reported	329	Primarily irrigation
	1993[#]	Not reported	407	Primarily irrigation
Florida (St Petersburg)	1995	16.5	16.5	Industrial
Australia	1994	1519	18	Industrial and irrigation
	2020[$]	2300	64	
Israel	1990/1	260	188	Agriculture
	1994[**]	232	194	
Japan[##]	1994[z]	10 900	85	Various (see above)
Tokyo city[##]	1995*	1 767	134	Various

[#] Mills and Asano (1996)
[$] Projections based on current trends: Thomas et al. (1997); however, implementation of the water reform schemes being advocated in Australia are expected to result in much more water reclamation taking place
[z] Maeda et al (1996)
[**] Shelef and Azov (1996)
[##] It is noted that the amount of water reused in 1995 for Tokyo is greater than that reused in the whole of Japan for the previous year. The Tokyo figure includes 102 x10^6 m^3/a that is reused in the wastewater treatment plants themselves for general cleaning, equipment cleaning and gas scrubbing. This application is not included in the list of national uses of reclaimed water.
* Nakazato and Kawamura (1997)
Tselentis and Alexopoulou (1996)

Comparing the calculated figure of 1 086 x 10^6 m^3/a for total TSE production with the estimated flow from major point sources in the DWAF study given above, it may be seen that this figure is probably conservative, but of the correct order.

Using the figure of 1 086 x 10^6 m^3/a for total production of TSE in South Africa, the reclaimed water usage of under 30 x 10^6 m^3/a therefore represents less than 3% of the total wastewater flow generated in the country. Although the international figures available are still rather scanty, it is helpful to gain a sense of perspective in situating South Africa in comparison with the countries where some data are available. From Table 2, it may be seen that the proportion of water reclaimed as a percentage of total wastewater produced ranges from less than 1% for Japan as a whole, to 84% for Israel, to 100% for a small city, namely St Petersburg, Florida, USA.

We may conclude, therefore, that South Africa, like Japan, is still at a very early stage of development in terms of its water reclamation efforts. Not surprisingly, Israel is in the forefront of national efforts at water reclamation, having implemented such projects for many years. It is important to note that while Australia, like South Africa, is currently reclaiming only a tiny fraction of its wastewater, policy proposals are being made through the Council of Australian Governments National Water Reform Task Force which are designed to boost efforts at water reclamation (Thomas et al., 1997).

Water quality considerations

The appropriateness of a reclaimed water supply for reuse depends on three factors:

- The quality to which the water is treated
- The consistency of treatment quality (i.e. can the reclaimed water user be guaranteed of a regular quality of water?)
- The cost implications of reuse.

A number of countries have set standards for acceptable qualities of reclaimed water in various reuse applications. Although the acceptability for reuse depends on the physical, chemical and microbiological quality of the water, the main concern regarding reuse of water in all applications is generally the microbiological quality of the water. Factors which affect the quality of reclaimed water include source water quality, wastewater treatment processes and treatment effectiveness, treatment reliability, and distribution system design and operation. An investigation into the standards applied for treatment of reclaimed water showed that standards for treatment vary from country to country, and depend on the proposed water reuse (Grobicki and Cohen, 1998). Certain standards also specify the required treatment technologies to be used in wastewater treatment, such as the World Health Organisation recommended microbiological quality guidelines for wastewater use in agriculture (Hespanhol and Prost, 1994), and the EPA guidelines for water reuse, published in 1998 (Crook and Surampalli, 1996).

To summarise, the standards required for each category of applications include the following:

- In irrigation, which is one of the most widespread uses for reclaimed water, required qualities depend on how irrigation is to be carried out (drip, subsurface or spray irrigation), and whether crops are to be consumed raw or cooked. Irrigation guidelines should, but do not always, take into account also the protection of farm workers and their families. Irrigation standards are generally set for faecal coliform concentrations ($\leq$ 200 fc/100 mℓ for fibre, fodder and seed crops, for instance, in the US EPA Guidelines) and, in some cases, for parasites and viruses.
- For direct and indirect potable, and domestic non-potable use, standards are more even stringent. Here total coliforms, viruses and parasites all need to be closely monitored. A number of additional physical and chemical water quality specifications also need to be met to ensure protection of users.
- No standards for reuse in industrial applications are generally set as the water quality required by industrial users will vary depending on the application for which the water is required. Some form of tertiary treatment may be necessary in order to meet the water quality requirements of the particular application.

The flow balance approach to water reclamation

If we examine the hydrological cycle, and the human water management loop, there are many points at which intervention could make more water available for use, without building new dams. Examples of such interventions which are being supported by the Water Research Commission include rainfall enhancement technology, and the eradication of alien species from catchments. Water demand management, water conservation and water saving devices also fall into this category of intervention.

However, increasing demand for water caused by urbanisation and industrialisation must also ultimately be matched by increasing intensity of land-based treatment and recycle, or in other words, water reclamation. This may make available for use a total amount of water which is many times the supply of raw water available, depending on the extent of losses from the water system, and the number of times water is recycled through the system.

There are many factors causing losses in the water loop, through leakage, evaporation, or use of water for irrigation, for instance. Only a fraction of the total urban and industrial water demand is typically produced as treated sewage effluent in South African cities and towns (between 35% and 65% (Grobicki and Cohen, 1998)). This fraction is termed the return ratio, which increases as the losses from the water system decrease. A principal aim of water demand management is to reduce such losses.

However, a complementary strategy for conserving water is to aim towards a “zero effluent” scenario whereby all of the treated sewage effluent is kept within the human water management loop, rather than being discharged to the surrounding environment. The city of St Petersburg in Florida, USA, has already achieved this objective, and provides a useful case study of what is possible for other municipalities [Internet 1]. This means reclaiming and reusing all treated sewage effluent produced. Looking at it another way, this intensifies the recycle, since water will continue to recycle until it is lost from the loop by leakage or irrigation. Such a scenario utilises the minimum of freshwater resources: essentially, raw water is only required to make up for the water losses from the loop.

Flow balance for a coastal town or city

Examining in more detail the arithmetic of the “zero effluent” scenario illustrates just how much more water is made available for urban and industrial use through full water reclamation. Figure 1 is a simple flow diagram representing a coastal town or city discharging its wastewater to sea, where the flows are shown as being fresh water (F), reclaimed water (R), losses from the system (L) and the discharge to sea (S).

The entire human water management system, i.e. the urban reticulation network, is a black box within this flow diagram, which takes water in, and then discharges it to the environment in various ways. All the losses from the system of various kinds are lumped together as the parameter L, including leakages, evaporation, and the use of water for irrigation, which effectively removes that water from the reticulation network. The residual discharge S is water which is treated and discharged into the environment from wastewater treatment plants. The zero effluent scenario under discussion is one in which the discharge S = 0. Thus all the water which would otherwise be discharged from the reticulation network is reclaimed and put back into the system in various ways, through the flow shown as R.

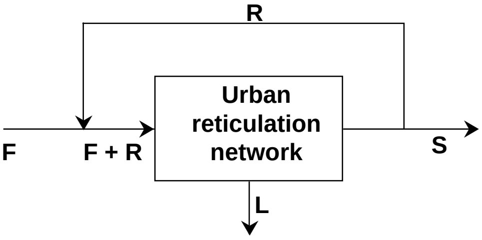

Figure 1

Flow balance around the urban reticulation network where

F = Fresh water
R = Reclaimed water (reused sewage and industrial effluent)
Q = F + R = Total water demand
L = Losses from the system (leakage, irrigation, and evaporation)
S = Discharge of effluent to surface water (sea)

The inflows to such a system must be equal to the outflows, hence a water balance over the entire system gives :

$$F = S + L \tag{1}$$

A water balance over the "black box" itself, which takes into account the flow of reclaimed water, gives:

$$Q = F + R = S + R + L \tag{2}$$

which is equivalent to the water balance shown in (1) above. However, this formulation is useful because it shows the total flow of water that is available to satisfy water demand in the system.

Now, introducing the return ratio r as a fraction, we have:

$$L = (1-r)\,(F + R) = (1-r)\,Q \tag{3}$$

Zero effluent scenarios at different return ratios

Scenario A. The average return ratio for urban areas in South Africa is 50% of total water usage (Grobicki and Cohen, 1998). Substituting the values $r = 0.5$ and $S = 0$, and solving the equations above, we find that :

$$R = F$$

Hence the total flow of water available to satisfy demand in the system (as in the left hand side of Eq. (2) above) is doubled. In algebraic terms :

$$Q = F + R = 2F$$

Put another way, a full water reclamation scheme which utilised all the available treated sewage effluent (the zero effluent scenario) would double the total inflow of water to the system, because the available inflow of reclaimed water would equal the existing inflow of fresh water to the system. Hence water demand could double from the level of demand before water reclamation was practised, without any additional pressure on fresh-water resources.

Scenario B. In major cities such as Cape Town or Durban, a higher return ratio of some 65% is currently achieved. Substituting the values $r = 0.65$ and $S = 0$, and solving the equations above, we find that:

$$Q = F + R = 2.86F$$

Hence if full water reclamation were practised, water demand could rise to nearly treble its current level, before new water resources would need to be tapped.

Scenario C. Taking the argument even further, we envisage a hypothetical situation where losses from the reticulation system are very tightly controlled, and comparatively little water is used for purposes like irrigation which take it out of the loop. The return ratio might then rise as high as 90%. Such a situation could potentially be engineered in a localised area such as a new industrial development. As before, by substituting the values $r = 0.9$ and $S = 0$, and solving the equations above, we find that:

$$Q = F + R = 10F$$

This means that the total available inflow into the system (F+R) is ten times the inflow of fresh water into the system. Effectively, as in all the scenarios above, the level of fresh water demand is that required to make up for the water losses from the system, whether by irrigation, leakage, evaporation or other processes taking water out of the human water management loop.

The intensification of water usage represented by the above scenarios (especially in scenario C) would obviously have to be matched by an intensification of treatment, to avoid the build-up of nutrients and salts in the system. However, with cutting-edge treatment methods such as membrane technology, scenario C is quite imaginable as a water management target in the twenty-first century. The implications of this are dramatic: on a localised basis, where very low water losses exist, water demand could increase up to ten-fold without requiring new fresh-water resources to be utilised.

Flow balances for an inland town or city

Effect of reclamation on river flows where TSE is returned to the same river

For an inland town or city, the water management system must be examined in a little more detail, as shown in Fig. 2, in order to be able to determine the effects of abstraction and return on the receiving water body. Here water is removed from a river (or dam) and used in various applications. A proportion of the water not lost during use or transport is sent to a sewage treatment plant and the effluent returned to the same river.

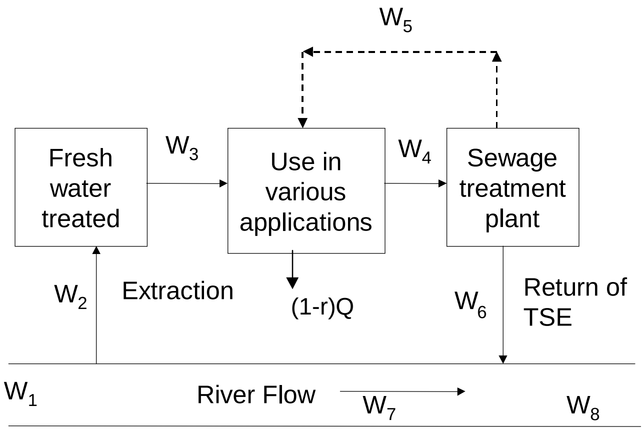

Figure 2

Withdrawal and return to the same river

In this diagram, the flow in the river is reduced by abstraction of stream with a volumetric flowrate W_2. A certain fraction of this water is consumed during use and the remainder is returned as stream W_6. Whilst reusing some of the TSE will result in a lowering of the return to river (i.e. less flow in W_6), it will also mean a lower abstraction rate from the river in W_2. Providing the amount of water reused is equivalent to the amount of fresh water which would be withdrawn from the river to meet demand, the reuse of TSE will imply no overall change in the flow in the river, and will not affect any downstream withdrawal. Thus, in the simplest case, reuse has no effect on the flow in the river.

To prove this, consider a demand of water of Q (given by ($W_3 + W_5$)). In a non-reuse scenario, $W_5 = 0$, $Q = W_3$ and, assuming no loss during water treatment, $W_3 = W_2 = Q$. Only a proportion of the fresh water supplied is returned to sewage; the remainder is used for irrigation, lost as leakage or otherwise consumed during use. Taking the fraction returned as r and assuming minimal loss during sewage treatment,

$$W_4 = W_6 = rW_3 = rW_2 = rQ \tag{4}$$

Furthermore:

$$\begin{aligned} W_8 &= W_7 + W_6 \\ &= W_1 - W_2 + W_6 \\ &= W_1 - Q + rQ \\ &= W_1 - (1-r)Q \end{aligned} \tag{5}$$

Now, if the illustrated recycle stream W_5 is implemented, a fraction (y) of the fresh-water demand stream is replaced with the recycled stream $W_5 = yQ$. W_4 remains unchanged since the overall volume supplied and hence treated has not been changed by the recycle step. Then:

$$W_2 = W_3 = (1-y)Q \tag{6}$$

$$\begin{aligned} W_6 &= W_4 - W_5 \\ &= r(W_3+W_5) - W_5 \\ &= r[(1-y)Q+yQ] - yQ \\ &= r[Q-yQ+yQ] - yQ \\ &= rQ - yQ \\ &= Q(r-y) \end{aligned} \tag{7}$$

And we have:

$$\begin{aligned} W_8 &= W_7 + W_6 \\ &= (W_1 - W_2) + W_6 \\ &= W_1 - (1-y)Q + (r-y)Q \\ &= W_1 - Q + yQ + rQ - yQ \\ &= W_1 - Q + rQ \\ &= W_1 - (1-r)Q \end{aligned} \tag{8}$$

Comparing Eqs. (5) and (8) shows that the flow in the river (W_8) remains unchanged despite the recycle step.

Take a hypothetical example, with fresh water demand Q of 850 Mℓ/d, the proportion of total water supplied which is returned sewage treatment of 60%, and a flow in a hypothetical river from which all of the water is removed of 1 000 Mℓ/d. Using this information, and the above relationships, Table 3 can be established. Also shown in Table 3 is a generic formula for calculation of the flows in the various streams, which may be used to provide estimates for situations other than that in the hypothetical example presented here.

It can be seen that the ultimate flow in the river (W_8) is unaffected by the recycle step. The maximum amount of water which can be returned to the system is the entire treated sewage effluent stream, giving a W_6 value of 0 (the zero effluent scenario). From Eq. (7):

$$W_6 = Q(r-y)$$

$$\begin{aligned} \text{for } W_6 &= 0, \\ Q(r-y) &= 0 \text{ or} \\ r-y &= 0 \end{aligned}$$

showing that for $W_6 = 0$, $r = y$. Thus, the maximum fraction of the total water demand stream which may be made up by reclaimed water (y) is equivalent to the proportion of the total water supplied which is returned to sewage treatment. This is as would be expected.

The implications of a zero effluent return scenario in the example above are that only 340/850 or 40% of the total demand is made up by fresh water withdrawn from the river. The remainder is made up by reclaimed water. Whilst the reduction in the withdrawal stream from the river has been shown to have no effect on the ultimate flow in the river (where return is to the same river), it does have potential quality implications for the flow of salts in the river. Furthermore, depending on the quality of water required by the reclaimed water users and the treatments used, it may imply a potential for reduction of treatment costs for fresh water. Water quality issues surrounding reclaimed water usage is discussed in detail below.

There is a further indirect benefit of water reclamation which may exist in this case. In practice, a large amount of water is lost in all of the steps presented in Fig. 2. The introduction of a reuse step may imply the laying out of new infrastructure to treat, transport and store the reclaimed water, with lower losses in all steps. Thus in a reuse scenario, the total water abstracted, W_2 is reduced by the amount of TSE recycled plus the reduction in water losses during the cycle. W_6 is reduced only by the amount of TSE reused. Hence the net overall abstraction from the river decreases, resulting in a net increase in flow in the river due to TSE reuse, over a non-reuse scenario.

TABLE 3
HYPOTHETICAL WATER FLOWS IN FIG. E1 FOR VARIOUS RECYCLE RATIOS, WITH W1 = 1000 AND r = 0.60

	W1	W2	W3	W4	W5	W6	W7	W8
General formula	**W_1**	**(1-y)Q**	**(1-y)Q**	**rQ**	**yQ**	**Q(r-y)**	**W_1-(1-y)Q**	**W_1-(1-r)Q**
No recycle	1000	850	850	510	0	510	150	660
10%	1000	765	765	510	85	425	235	660
20%	1000	680	680	510	170	340	320	660
30%	1000	595	595	510	255	255	405	660
40%	1000	510	510	510	340	170	490	660
50%	1000	425	425	510	425	85	575	660
60%	1000	340	340	510	510	0	660	660

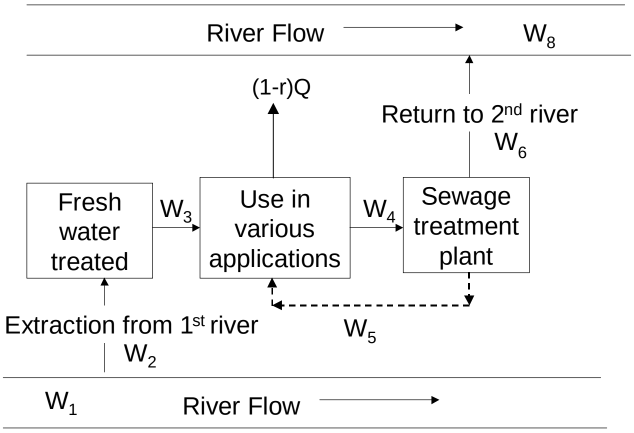

Figure 3
Return to a water body other than that from which water has been abstracted

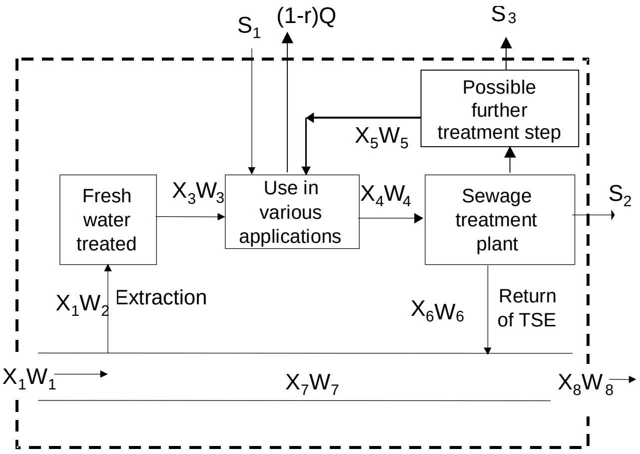

Figure 4
Simple withdrawal – return scenario showing salt loadings

Effect of reuse on river flows where TSE is returned to a different river

While the Water Act of 1956 required discharge of water back into the river from which the water was abstracted, numerous exceptions to this requirement were approved, with water being returned to rivers other than those than from which withdrawal took place. Figure 3 is a schematic representation of this situation.

In this case, reuse results in different consequences to those explored in the section **Effect of reclamation on river flows where TSE is returned to the same river**. A reuse scheme W_5 implies a reduction in return of treated sewage effluent to River 2, which is shown above as W_6. The reuse results in a reduction in demand for fresh water, W_2 and hence an increase in flow in River 1. The possible implications associated with a reduction in flow in River 2 need to be evaluated for each individual case, especially when downstream extraction from the discharge point occurs in River 2.

Once again, new infrastructure laid out for the purposes of reuse systems may imply lower losses through the system, and hence the reduction in W_6 may be less than the reduction in W_2. This results in an overall conservation of water.

Salt balances for an inland town or city

The role of treated sewage effluent in determining river water quality and quantity

The importance of returning flows of treated sewage effluent, with respect to the water quality and the salt balance within a river, is a complex issue. There are two possibilities:

- In instances where the treated sewage effluent which is returned is of higher quality than the water flowing in the river, the return flow is considered to be necessary in order to dilute the water in the river. In the Jukskei River/Hartbeespoort Dam system, nutrients and bacteriological problems in this system are caused largely by polluted stormwater runoff from developed areas, as opposed to the TSE entering the system (Hinch, 1998). The TSE in fact serves to dilute the stormwater before it enters the dam, and the the reduction of return flows would therefore be considered to be undesirable.
- On the other hand, in some cases high salt loadings in the TSE are diluted by pumping the treated sewage effluent into a better quality river. Water qualities have deteriorated in a number of South African rivers receiving large quantities of effluent, mainly due to salinity build-up which results from the addition of salts through most uses of water, as well as to eutrophication due to the addition of nutrients in the TSE (DWAF, 1997). Water quality in these rivers must be carefully managed through the control of effluent standards and by means of blending. In these cases, water reclamation could assist in reducing the effluent load into the receiving river or water body.

Effect on salt loading and concentration when TSE is returned to the same river

Each of the possibilities outlined above will be analysed in turn, by means of a mass balance on the salt.

In Fig. 4 below, W represents the flow in a stream (in, say, ℓ/h), while X represents the salt concentration in the stream (g/ℓ). XW thus represents the mass flow rate of salt in g/h. The S terms represent a salt addition or removal to the water in g/h as follows:

- S_1 is the salt load entering the treatment plant which results from normal use of the water, e.g. domestic, commercial or industrial use.
- S_2 is the removal of salt during sewage treatment, through biological treatment and desludging, to get the effluent stream to meet the quality requirements of the receiving water body.
- S_3 is salt removed from the TSE in a further treatment step, to meet the water quality requirements of the user. Certain users may require TSE treated to the equivalent of potable water, while for others the quality of the TSE as is may be sufficient. Kriel (1995) proposes membrane treatment by, for example, reverse osmosis, as one option to carry out this step. In his analysis, a concentrated brine is returned to the sewage treatment plant for further treatment, while the desalinated stream is reused. This represents one specific scenario, while the case presented below is more generalised.

From previous discussions, reuse of TSE implies a reduction in W2 and hence an increase in W_7. W_8 is not, however, affected.

The salt balance is now analysed in a manner similar to that used for the water balance. Where there is no recycle stream, X_5W_5

= 0. From the discussion used for the development for Eq. (4) :

$$\begin{aligned} W_2 &= Q \text{ and} \\ X_1W_2 &= X_1Q \end{aligned} \tag{9}$$

Since the amount of salt added or removed in conventional water treatment plants (e.g. by the addition of alum, flocculation and chlorination) is negligible, we have :

$$X_3W_3 = X_1W_2 = X_1Q \tag{10}$$

Then, from Eq. (4):

$$W_4 = W_6 = rW_3 = rW_2 = rQ,$$

We get:

$$\begin{aligned} X_4W_4 &= X_3rW_3 + S_1 \\ &= rX_1Q + S_1 \end{aligned} \tag{11}$$

With no recycle, $X_5W_5 = 0$ and

$$\begin{aligned} X_6W_6 &= X_4W_4 - S_2 \\ &= rX_1Q + S_1 - S_2 \end{aligned} \tag{12}$$

Finally:

$$\begin{aligned} X_8W_8 &= X_7W_7 + X_6W_6 \\ &= X_1W_1 - X_1W_2 + X_6W_6 \\ &= X_1W_1 - X_1Q + rX_1Q + S_1 - S_2 \end{aligned} \tag{13}$$

Now, introducing a fraction y which is recycled, from Eq. (6):

$$W_2 = W_3 = (1-y)Q \tag{14}$$

we get:

$$X_1W_2 = X_1(1-y)Q \tag{15}$$

Now Eq. (10) becomes:

$$X_3W_3 = X_1W_2 = X_1(1-y)Q \tag{16}$$

With a recycle of stream W_5 equal to yQ, Eq. (11) gives:

$$\begin{aligned} X_4W_4 &= r[X_3W_3 + X_5W_5] + S_1 \\ &= r[X_1(1-y)Q + X_5(yQ)] + S_1 \end{aligned} \tag{17}$$

and:

$$\begin{aligned} X_6W_6 &= X_4W_4 - S_2 - X_5W_5 - S_3 \\ &= r[X_1(1-y)Q + X_5(yQ)] + S_1 - S_2 - X_5(yQ) - S_3 \end{aligned} \tag{18}$$

S_2 is the salt removed during sewage treatment. Assuming that the technology is robust enough to produce the same quality effluent despite the increased salt loading from reuse of the TSE stream, and assuming no water losses during sewage treatment, we have:

$$S_2 = X_4W_4 - (X_6(W_6+W_5)) = X_4W_4 - X_6W_4 \tag{19}$$

It is noted from the outset that this assumption is contestable. Where the user of TSE requires water of potable standards, the further treatment step following sewage treatment (removing salt stream S_3) provides water of the required quality. However, when the reclaimed water is of a lower quality than the fresh water which it is replacing, the stream entering sewage treatment will contain a higher salt loading than with no reuse. Should the sewage treatment step not be robust enough to treat the more concentrated stream to the same discharge values as in the non-reuse scenario, the potential exists for a build-up of salts within the system. This may result in an effluent too concentrated for either reuse or discharge, without further expensive treatment. In addition, the reuse loop may result in the build-up of undesirable substances (e.g. endocrine disrupting chemicals) (Haarhoff, 1999). This situation is very complex and requires careful consideration of technologies all along the flow path. For this reason it is not considered further here.

Continuing, by substituting Eq. (17) into (19), and since $W_4 = rQ$, this gives:

$$S_2 = r[X_1(1-y)Q + X_5(yQ)] + S_1 - X_6rQ \tag{20}$$

S_3 is the salt removed from the TSE by tertiary treatment, to bring it to a quality which is acceptable by reclaimed water users. Thus:

$$\begin{aligned} S_3 &= X_6W_5 - X_5W_5 \\ &= (X_6 - X_5)W_5 \\ &= yQ(X_6 - X_5) \end{aligned} \tag{21}$$

Finally, the downstream salt loading in the river is given by:

$$\begin{aligned} X_8W_8 &= X_7W_7 + X_6W_6 \\ &= X_1W_1 - X_1W_2 + X_6W_6 \\ &= X_1W_1 - X_1(1-y)Q + r[X_1(1-y)Q + X_5(yQ)] + S_1 - \\ &\quad S_2 - X_5(yQ) - S_3 \\ &= X_1W_1 - X_1Q + X_1Qy + X_1Qr + X_1Qry + rX_5yQ + \\ &\quad S_1 - [r[X_1(1-y)Q + X_5(yQ)] + S_1 - X_6rQ] - X_5yQ \\ &\quad - yQ(X_6 - X_5) \end{aligned} \tag{22}$$

Where y = 0, this reduces to Eq. (13) as expected.
Rearranging and simplifying of (22) further gives:

$$X_8W_8 = X_1W_1 + X_1Q[y - 1 + 2ry] + X_6Q(r-y) \tag{23}$$

The salt flow in the river downstream of discharge is thus a function of the following variables:

X_1 and W_1 = the initial flow and salt concentration in the river
Q = the water demand
r = the fraction of the water supplied which is returned to sewage treatment
y = the proportion of the demand stream supplemented by reclaimed water
X_6 = the concentration of salts in the stream returned to the water body

Now, for the purposes of demonstrating the effect of a reuse step on the ultimate salt loading in a hypothetical river from which withdrawal takes place, the following parameters are set to be constant, as per the example given earlier:

W_1 = 1000 Mℓ/d
Q = 850 Mℓ/d
r = 0.61

This was done for two different scenarios. Scenario A is when the salt concentration in the river is significantly higher than that in the discharge stream. Taking X_1 as 1 100 mg/ℓ* and X_6 as = 91 mg/$\ell^{\#}$

TABLE 4
CONCENTRATION OF SALT DOWNSTREAM OF DISCHARGE WHEN THE CONCENTRATION IN THE RIVER IS HIGHER THAN THAT IN THE DISCHARGE STREAM

y	X_8W_8 (kg/d)	W_8 (Mℓ/d)	X_8(mg/ℓ)
0%	2.11E+05	660	320.32
10%	4.09E+05	660	620.27
20%	6.07E+05	660	920.21
30%	8.05E+05	660	1220.16
40%	1.00E+06	660	1520.11
50%	1.20E+06	660	1820.05
60%	1.40E+06	660	2120.00

TABLE 5
CONCENTRATION OF SALT DOWNSTREAM OF DISCHARGE WHEN THE CONCENTRATION IN THE RIVER IS LOWER THAN THAT IN THE DISCHARGE STREAM

y	X_8W_8 (kg/d)	W_8 (Mℓ/d)	X_8(mg/ℓ)
0%	2.78E+05	660	420.45
10%	2.63E+05	660	398.56
20%	2.49E+05	660	376.67
30%	2.34E+05	660	354.77
40%	2.20E+05	660	332.88
50%	2.05E+05	660	310.98
60%	1.91E+05	660	289.09

the results shown in Table 4 were established. [* *Water in contact with palaeozoic and mesozoic sedimentary rock contains a maximum possible TDS of 1100 mg/ℓ; this value is used as a worst case scenario (South African Water Quality Guidelines).* #*Average values in effluents from different Umgeni Water Wastewater Treatment Works range from 48 to 182 mg/ℓ. The value used here is an average from all their treatment plants as given in their 1996/97 Annual Report*].

It was shown earlier that the maximum value of y which can theoretically be supplied is equal to r. From this table, it is seen that the recycle step significantly increases the concentration of the salts in the final river stream. This effect:

- decreases as the flow in the river increases and/or the abstraction rate decreases, as the effect of the return flow on the salt loading is diminished as the flow in the river increases;
- increases significantly as the concentration of salts in the river increases, as the return flow, which assists in diluting the river stream, is reduced as y increases.

In a zero effluent scenario, where r = y = 0.6, the salt concentration is over six times higher than in a non-reuse scenario. This shows the significance of the recycle step in diluting the flow in the river. Clearly, if the flow in the river is much greater than the extraction rate, as would be expected in reality, this effect would be reduced accordingly.

Scenario B is when the salt concentration in the river is significantly lower than that in the discharge stream. Taking X_1 as 150 mg/ℓ and X_6 as = 500 mg/ℓ the results shown in Table 5 were established.

Now, the effect of an increase in recycle is to drop the salt flow in the river. This is as would be expected: since the concentration of salts in the discharge stream is higher than in the river, the less water that is returned to the river, the lower the salt flows in the river. In a zero discharge scenario, the salt flow in the river is significantly reduced – no return to the river implies no extra salt loading. Again, the impact of the return stream on the salt concentration in the river is reduced as the flow in the river increases. The effect in all cases is noted to be less so than in the previous table as the difference in concentrations between the river and return stream are less pronounced in this case.

In summary, therefore, the effect of the water reclamation depends on the concentration of salts in the river relative to that in the return stream. The return stream will either dilute or increase the salt concentration in the river. Where the return stream is more concentrated, the salt concentration in the river will drop. Where the return stream is more dilute, the concentration in the river will be higher than if no water reclamation was taking place. In either case, however, the benefits in terms of reducing raw water consumption remain as outlined in the previous section.

Effect on salt loading and concentration when return is to a different river

The situation where return is to another river is considered in Fig. 5 below. Since no discharge to river 1 is occurring, $X_1 = X_7$ and hence salt concentrations in the river remain unchanged. The flow is, however, higher in a non-reuse situation as discussed previously, and hence the total salt loading, X_7W_7 is higher.

The salt balance for River 2 is:

$$X_8W_8 = X_9W_9 + X_6W_6$$

When a reuse step for TSE is introduced,

- W_6 is reduced
- X_9W_9 remains unchanged.

Consider a balance over the dashed square in Fig. 5:

$$X_6W_6 = X_3W_3 + S_1 - S_2 - S_3$$

Assume in the above equation that S_1 and S_2 remain unchanged in a reuse scenario. X_3W_3 will drop as the requirement for fresh water drops. The value of S_3 ranges between 0 and the drop in X_3W_3. Thus, regardless of the value of S_3, X_6W_6 drops. The total salt load in River 2, X_8W_8, thus also drops in a reuse scenario, as compared to a non-reuse scenario.

Discussion on return to rivers

The return of treated sewage effluent to rivers is regarded in inland areas of South Africa as an important aspect of water management, especially with regard to downstream availability of raw water for further abstraction. This is termed “planned indirect reuse” and was implemented through the Water Act of 1956 (Odendaal et al., 1998). With increasing water demand, the volume of return flows to rivers and dams is increasing steadily. The Hartbeespoort Dam, for instance, already receives equal volumes of natural run-off and

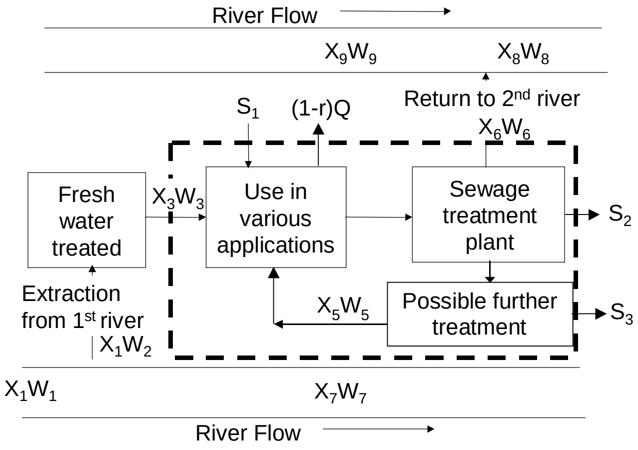

Figure 5

Salt balance where return is to a river other than that from which withdrawal has occurred

effluent return flows. By the year 2020, it is projected to receive effluent return flows which are double the natural run-off. Increasing salt levels in major rivers such as the Vaal can be ascribed to the planned indirect reuse philosophy (Odendaal, 1990). At present a suite of mathematical models are used to simulate the hydrology of the Vaal River and model the water quality, especially with regard to the salt content (Herold, 1981). However, investigating the direct reclamation of water would require different assumptions to be made. Closing the urban water management loop prior to discharging treated sewage effluent to surface waters carries many benefits, as shown above. The usage of water can be intensified to reduce raw water consumption significantly, compared to projected growth in water demand. Evaporation losses are lower, as are treatment costs, and there may often be beneficial spinoffs in terms of water quality and ecological sustainability of the receiving water bodies. The major hurdle discouraging local authorities and water services providers in inland areas from considering direct reclamation is the existing system of planned indirect reuse. The question of providing infrastructure for such reclamation, however, is a second hurdle which needs to be overcome.

In order to overcome these hurdles, there must to be additional incentives to local authorities and water services providers to consider water reclamation seriously, certainly in inland areas. The concept of reusing treated sewage effluent directly needs to become an integral part of water conservation or water demand management strategies. In coastal areas, especially in metropolitan areas such as Cape Town and Durban, this is already beginning to take place. In order to implement water reclamation to a significant level nationwide, there would need to be a re-orientation on the part of the Department of Water Affairs and Forestry and of the major water services providers who operate in inland areas, as well as the local authorities involved. Such a re-orientation would need to be based upon an investigation of the treatment and distribution costs of the present system, as compared to a system of direct reuse of treated sewage effluent. Detailed salt balances and nutrient balances would need to be carried out, together with the system analysis and water balances normally used in water resource management.

Ultimately the debate which opens up, with regard to return to rivers versus direct reuse of TSE, revolves around two quite distinct points :

- Firstly, issues surrounding ownership of water. Treated sewage effluent which is to be returned to rivers and dams has up until now been regarded as public water and hence there has been a perception that all TSE should be returned to public water-courses. Within the Water Services Act of 1997, however, it is clear that the local water services provider has responsibility for the water until it is returned to a public water-course. Decisions to reclaim water can therefore be made at a local level, by the water services provider alone. Tariff levels are potentially a contentious issue in this situation.
- Secondly, environmental uses including the instream flow requirement of rivers and levels in dams and lakes. The discharge of TSE into rivers and, ultimately, dams also represents significant "environmental" usage of water. However, this assertion has usually been made in a context where instream flow requirements have not yet been calculated. There may also be strong concerns in certain cases about the ecological damage caused by returning excessive flows of TSE to rivers, with regard to water quality as well as flow volumes.

The implementation of the National Water Act of 1998 will doubtless cast more light on both of these points. In the long term, water services providers will need to negotiate with the relevant catchment management authority or authorities (where more than one catchment is involved) as provided for in the new Act, in order to determine volumes of discharge of treated sewage effluent, as well as water abstraction. Water reclamation projects would then form part of such negotiations. In the short term, however, there appears to be strong institutional resistance to the concept of direct water reclamation in inland areas. Implementation of the new permitting arrangement for discharges under the National Water Act may therefore be the most powerful persuasive force which will cause local water managers to look for alternatives to the discharge of treated sewage effluent into rivers.

Conclusions

This paper has argued the case for direct water reclamation, and the need for the intensification of land-based treatment which this implies. The role of land-based treatment, seen from this perspective, is essentially to remove the substances and compounds which accumulate in the water during use. Water's role as a carrier of substances is perhaps the least important of its functions, many of which are essential to support life itself, but this role is currently still the major one in its urban context, in terms of volume. However, it is a low-value role, which is no longer appropriate.

Redefining the value of water in the new National Water Act of 1998 will help to create a shift in perception, and will increase the value of water (as well as the price of water, which is not necessarily synonymous with value). This important legislative development, together with the practical consequences in terms of increasing tariffs, will undoubtedly change the ways in which water is used in South Africa. Hand-in-hand with this should go efforts to increase the extent of water reclamation taking place. It is important to recognise that only a small fraction of the water supply, treated to potable level, is actually used for drinking, and hence both treatment and distribution costs, as well as losses in the system, could be saved through water reclamation. Such water reclamation efforts will push up the threshold of sustainable water use, to support much-needed economic and social development in South Africa.

In the initial phase of promoting water reclamation, coastal towns and cities should be targeted. Zero effluent discharge to the marine environment is a feasible goal which has already been achieved elsewhere in the world. However, the water management systems in inland areas should also be re-examined for their water reclamation potential, carrying out thorough salt and nutrient balances as well as flow balances for specific areas. The current practice of planned indirect reuse through return to rivers is costly in terms of losses through evaporation, and additional treatment costs, as well as often being damaging to riparian eco-systems. As shown in this paper, the flow balance approach demonstrates the proportion of raw water demand which can be replaced by water reclamation schemes. There are potentially also large savings in treatment costs in reclaiming water directly for industrial use, as well as for irrigation. Both in terms of cost and in terms of conserving fresh-water resources, water reclamation is bound to become a vital part of South Africa's water management strategy for the future.

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