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THE UNIVERSITY OF NEW SOUTH WALES
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Manly Vale N.S.W. Australia

EVALUATION AND IMPROVEMENT OF QUALITY CHARACTERISTICS OF URBAN STORMWATER

by

Ian Cordery

Research Report No. 147
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SCHOOL OF CIVIL ENGINEERING

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Some of the stormwater samples were subjected to simple settling in the laboratory for durations of up to one hour. For a typical urban catchment these laboratory tests show that on an annual basis, short duration settling of stormwater could remove amounts of pollutants comparable to the amounts which could be removed by tertiary treatment of secondary sewage effluent from the same catchment. The cost of settling storm runoff would probably be far less than tertiary treatment of secondary sewage effluent.

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SYNOPSIS

Stormwater samples collected from three urban catchments in Sydney, show that in separately sewered areas the surface runoff has a greater concentration and carries a greater total load of pollutants, than effluent from secondary sewage treatment plants. Pollution and nutrient indicators are highly concentrated in the "first flush" at the start of urban storm runoff, but these concentrations fall rapidly to quite low levels during the passage of each flood. An important exception to this trend is phosphate. The phosphate concentration remains approximately constant during each flood. Whenever the discharge increases sharply the concentrations of suspended solids and phosphate increase slightly. However, the concentrations of BOD and ammonia do not usually increase after the first flush unless a later increase in discharge is extremely rapid. Faecal coliform concentrations in flood flows are usually between one and two orders of magnitude less than for raw sewage.

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KEYWORDS: Floods, water quality, water pollution, settling, treatment, sewage effluent, urban runoff, discharge, surface runoff.

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1. INTRODUCTION

The change from rural to urban land-use conditions has very large effects on streams (Ref. 7). However, almost no data on these effects are available for Australian conditions. Considerable data are available for some of the effects of urbanisation on streams for the United States and some data are available for the United Kingdom. Most of the published studies are applicable only to the areas in which they were conducted. Very little progress has been made in attempting to extend the results of studies of local areas to obtain a general theory of the effects of urbanisation. Numerical data are given of the changes in flood magnitude, sediment load and water quality as a result of urbanisation. However the lack of general understanding of the processes involved in these changes means that the published information really only provides qualitative indications of the changes that can be expected when changing the land use of an area from rural to urban conditions.

The major effects on streams of urbanising rural land can be summarised as follows:—

i) Flood discharges are increased. Floods which occur frequently, with return periods of the order of 1 year are usually increased by about three times. Larger floods are increased by much smaller amounts and it is thought that extreme events, say with return periods of 100 years or more, are probably not increased to any noticeable extent (Ref. 14).

ii) Runoff volumes are increased by up to two times. This increase factor seems to be highly dependent on the soil types and underlying geology (Ref. 7).

iii) During the change from rural to urban conditions sediment loads increase astronomically. Hugh volumes of sediment are removed from cleared land surfaces during the construction period (Refs. 9, 28). After construction is complete the sediment load tends to settle back to a value similar to that observed under rural conditions.

iv) Surface water quality, which is the main subject of this report, generally deteriorates when an area changes from rural to urban conditions. Large volumes of sewage, which are not present in rural areas, must be removed from urban areas. In addition, the surface runoff, or stormwater, which is more plentiful in urban areas than under rural conditions, is usually of poor quality, being roughly equivalent to the effluent from sewage treatment plants which provide primary and secondary treatment of domestic sewage (Ref. 4).

In recent years considerable attention has been given to prevention of flood damage from the large discharges that occur for short durations in urban areas. In just a few areas attention has been given to reduction of sedimentation during development of urban regions. Considerable interest has developed recently in the pollution of water resources by sewage. Local authorities are being required to produce higher quality effluents by a pollution conscious public. Hence a great deal of attention is currently being given to the quality of effluents from sewage treatment plants that are to be discharged into the environment, particularly inland waters. It is interesting to note that recent overseas work has shown that the pollution load exerted on receiving water bodies by sewage effluent may, in fact, not be the major cause of stream degradation. It has been shown that the pollution load exerted by urban stormwater runoff may be as high, or even much higher than the load exerted by secondary sewage treatment plant effluent (Ref. 27).

These overseas findings have very significant implications for the allocation of resources for water pollution control. It is possible that it would be more beneficial to attempt to provide simple treatment of urban stormwater than to provide higher levels of treatment of sewage effluent. However, to date the most common mode of reaction by local authorities to public pressure concerning water pollution has been to attempt to improve the quality of sewage effluent.

The purpose of this report is to present urban stormwater quality data collected over a period of 12 months at three sites in Sydney. Special emphasis is given to the distribution of the various quality parameters during the passage of floods.

The possibility of obtaining worthwhile benefits from the treatment of urban stormwater is also examined in relation to the data obtained for the Sydney catchments. A simple comparison is made of the effectiveness of two possible methods of reducing the water pollution load discharged from an urban area. The first method is to provide tertiary treatment of the secondary sewage effluent currently discharged from the area and the second is to provide primary treatment of stormwater.

2. QUALITY OF URBAN STORMWATER

Very little published data is available on the quality of urban runoff in Australia. The data that has been published (Ref. 10) relates only to low flow conditions and hence is not really representative of the total flow.

A large amount of urban stormwater quality data is available for the U.S.A. From this data considerable understanding of quality aspects of urban runoff has been obtained, but very little insight has been gained of the processes involved in the contamination of rainwater once it has touched the ground surface. Sartor and Boyd (Ref. 24) have shown that over half the pollution load of urban stormwater is associated with particles of 200 microns and smaller. Most of these small particles are usually found on the street surface within 20 cm of the curb. Current street sweeping technology can only remove a small proportion of the particles of this size and these authors conclude that the only way to prevent considerable pollution of receiving waters would be to treat the urban stormwater.

It is well known that early in a storm a flushing effect often occurs, when debris which has accumulated in dry times is washed into the drainage system. At the same time accumulations of material in the drains themselves are stirred up and swept along the pipe or channel system. It is also well known that the pollution load is much higher during flood flows than under low-flow conditions. However, the data obtained so far have not, in general, been sufficient to provide a clear understanding of the overall processes involved in the pollution of stormwater from which reliable, generally applicable predictive models can be derived.

The most readily observed and measured indicator of pollution in stormwater is the suspended solids concentration. A more definitive indicator of general pollution of water is the oxygen demand. Nutrient indicators such as phosphates and nitrates are also important in that they give some indication of the likelihood of eutrophication of water bodies. The other quality variables which appear to be of most significance for planning and water resources purposes, as well as for general pollution abatement are pathogen concentrations and the presence of toxic substances.

Several writers have shown that higher concentrations of some pollutants are found in urban stormwater than occur in raw domestic sewage.

The general finding appears to be that urban stormwater is at least as heavily polluted as the effluent from secondary sewage treatment plants. Some details of published data are shown in Table I. This is not an exhaustive list but is considered to be representative of overseas data.

The BOD of raw sewage is normally in the range of 200-400 mg/l. Secondary treatment plant effluent concentration would usually be in the region of 20 mg/l. Stormwater sampled by Bryan (Ref. 4) and Burm and Vaughan (Ref. 6) had mean BOD concentrations of 31 mg/l and 29 mg/l respectively with individual values ranging as high as 238 mg/l. Pravoshinsky and Gatillo (Ref. 23) found values as high as 223 mg/l for Minsk, Russia but Angino et al. (Ref. 2) reported low concentrations, the mean value being 6.9 mg/l and the upper limit 12.3 mg/l. Viessman (Ref. 25) has reported a mean BOD of 17 mg/l with a highest observation of 173 mg/l.

Concentrations of suspended solids are commonly very high in urban stormwater, often much higher than in raw domestic sewage. In raw sewage suspended solids concentrations may be up to 600 mg/l but more usual values are in the region of 300 mg/l. In a number of studies suspended solids and total solids are not differentiated. Burm and Vaughan (Ref. 5) found the mean annual concentration of suspended solids at Ann Arbour, Michigan to be 1360 mg/l with a maximum observed value of 11 900 mg/l. Bryan (Ref. 4) quotes a mean value of total solids of 3900 mg/l with an extreme sample of 13 900 mg/l for Durham, North Carolina. McElroy and Bell (Ref. 18) quote a number of studies in which the mean suspended solids concentration of stormwater exceeded 2000 mg/l. The most extreme value quoted was of a sample containing over 36 000 mg/l of solids.

Nutrient loading of urban stormwater has not been investigated as extensively as have the pollution indicators. Kluesener and Lee (Ref. 15) have shown that concentrations of total phosphate and ammonia nitrogen of about 2 mg/l are fairly common in the first flush. Average concentrations during storms were generally lower, about 1.0 mg/l and 0.5 mg/l respectively for phosphate and ammonia with upper limits of about 3.5 mg/l and 1.3 mg/l respectively. Viessman (Ref. 25) quotes mean values and ranges for phosphate of 1.1 mg/l, 0.02-7.3 mg/l, and for inorganic nitrogen of 1.0 mg/l and 0.1-3.4 mg/l respectively.

Sewage effluent has frequently been thought to be the major contributor of nutrients to streams and lakes near urban centres but

Whipple et al. (Ref. 27) have shown that urban stormwater may contribute quantities of nutrients at least equal to those which derive from sewage effluent. These authors quote a maximum phosphate concentration of 4.3 mg/l with the average over a period of several days of about 2 mg/l.

Bacteria contained in storm runoff are usually estimated by considering the presence of the coliform group, particularly E. coli. Many recent U.S. studies have involved taking coliform counts, the presence of E. coli being a definitive indicator of recent faecal pollution. Fairly typical coliform densities in urban stormwater seem to be about 10^6 and 10^5 organisms/100 ml respectively for total coliforms and E. coli (Refs. 3, 5, 11, 21, 22).

Considerable amounts of lead from vehicle engines have been observed in urban stormwater. Bryan (Ref. 4) found that the lead concentration is related to traffic density.

3. SAMPLING OF STORMWATER IN SYDNEY

3.1 Catchments

Stormwater samples have recently been collected from three separately sewered catchments in Sydney. Two of these catchments, Musgrave Avenue Drain and Bunnerong Storm Water Channel (SWC), are in Sydney's Eastern Suburbs where the soils are predominantly sandy, underlain by considerable depths of sand with occasional outcrops of sandstone. The third site is on Powells Creek at Strathfield where the soils are of the Wianamatta group—clays underlain by shale. All three catchments are primarily residential areas, although Bunnerong SWC and Powells Creek contain minor commercial developments such as shopping centres. Over 20% of Musgrave Avenue catchment is parkland. The location of the catchments is shown in Fig. 1 and a brief summary of the characteristics of the catchments is given in Table II.

Water samples were obtained adjacent to stream gauging stations on each of the catchments. The three gauging stations are in brick and concrete lined open channels, just downstream of the emergence of water from pipes or enclosed concrete conduits. Streamflow measurements have been made continuously for over ten years on Powells Creek and Bunnerong SWC. A staff gauge in Musgrave Avenue Drain permits the estimation of discharges when samples are being taken.

Automatic rainfall recorders are located in Musgrave Avenue and

Powells Creek catchments but the records from these instruments were not very reliable.

3.2 Collection of Water Samples

Water samples were collected during low flow times, and during the passage of floods between June 1975 and May 1976. Twenty samples were obtained from low flows, and about 110 samples were obtained during the passage of 15 floods. Ten floods were sampled in Musgrave Avenue Drain, three in Powells Creek and two in Bunnerong SWC.

All samples were instantaneous, "grab" samples. No automatic sampling equipment was available. The samples were collected in large-mouthed plastic or glass containers of about two litres capacity, which, under flood flow conditions took less than one second to fill. In some cases four litre samples were obtained. The samples were "grabbed" so that they would be as representative as possible of the flow at the time. The depth and velocity of flood flows at the points of collection varied from a few centimetres and about 0.2 ms^{-1} to 0.6 metre and 2.5 ms^{-1}. Low flow samples were obtained at points where all or most of the flow could be caught, for example at a step in a channel or at the outflow from a pipe into a channel.

Stormwater samples were tested for their constituent parameters using various standard tests. A wide range of equipment was available in the Public Health Engineering laboratory in the School of Civil Engineering, The University of New South Wales. In general the simplest and quickest (in terms of operator time) reliable methods were used. The tests used are detailed in Table III.

4. QUALITY PARAMETERS OF SAMPLED STORMWATER

4.1 Low Flow Data

A summary of the quality parameters for samples obtained under low flow conditions is given in Table IV. The mean values shown apply to the individual samples and are not flow weighted means. It can be seen that on some occasions the BOD and suspended solids loads are almost as high as would be expected for raw sewage. The highest dry weather BOD observed was 135 mg/l and the highest suspended solids concentration was 295 mg/l.

4.2 Flood Flow Data

Flood flow data are summarised in Table V. As in Table IV, the mean concentration of each parameter shown in Table V is the mean of the individual instantaneous samples. For comparison purposes typical quality data for raw sewage and secondary effluent from the St. Marys Water Pollution Control Plant in Sydney are also shown in Table V. The plant at St. Marys, which treats domestic and industrial wastes from a separately sewered area, comprises settling tanks and activated sludge treatment. The sewage is primarily drawn from residential areas with some light industry.

In Table V it can be seen that whilst the mean suspended solids concentration of the urban stormwater is the same as for raw sanitary sewage, individual values significantly higher than for raw sewage often occur, with a maximum value of 1400 mg/l being observed. The BOD of urban stormwater was consistently higher than for secondary sewage-treatment effluent. The maximum BOD concentration observed for the stormwater was 145 mg/l and the mean values observed on the two sandy catchments were almost double that for typical secondary treatment plant effluent.

Some of the other stormwater parameter concentrations are also quite high compared with secondary sewage effluent. However the suspended solids concentrations are low when compared with some of the U.S. data quoted above. It is possible that the large differences in suspended solids concentrations between U.S. and Australian data may be due to differences in stormwater drain design. In parts of the U.S.A. large catch drains (in Australia these would probably be called sumps) which accumulate debris are located at most inlets to the pipe system. Scouring of these under high flow conditions could account for suspended solids concentrations as high as 13 000 mg/l.

The phosphate and nitrogen concentrations are low compared with secondary sewage effluent but they are quite high when compared with the overseas data given in Table I. However the nitrate concentrations for Sydney stormwater are very low when compared with the overseas data.

It is of interest to note the high coliform counts in the stormwater. The erratic behaviour of the low flow coliform counts could indicate either random pollution of the water by animals or the connection of sewers from one or two households to the surface drains. The occasional high ammonia values may support these conclusions. During high flows the coliform counts tend to be slightly lower than under low flow conditions, but occasional very high values occur.

Some parameters, such as sulphate, alkalinity, hardness, chloride and silicate were only measured from a few samples. Further samples were not tested for these parameters as it was considered they did not provide any worthwhile information on the pollution of urban stormwater.

5. VARIATION OF QUALITY PARAMETERS WITH DISCHARGE

Discharge, concentration and load data from six floods in Musgrave Avenue Drain are shown in Figs. 2 to 7. Data for three floods in Powells Creek and one flood in Bunnerong SWC are shown in Figs. 8 to 11. Rainfall data are shown for those floods for which they are available. Incomplete data were collected from 6 other floods. These incomplete data are listed in Table VI.

The data shown in Figures 2 to 11 clearly show many quality characteristics of urban stormwater. For instance Fig. 2 shows the "first flush" with high concentrations of pollutants resulting from two, early, light showers. However it also indicates the significant increase in pollutant concentration whenever the discharge increases rapidly, as shown at 1725 hours and 1755 hours. The pollution concentration generally decreases with duration of rainfall, but as shown in Figs. 2b and 2c, the rate of transmission of pollutants (grammes/s) by the system is much more dependent on the rate of flow than on the concentration. High concentrations at 1535 hours and 1610 hours associated with flows of less than 100 l/s resulted in the movement of a total of only 20 kg of suspended solids and 3 kg of oxygen demand (expressed as 5 day, 20°C BOD). However the higher flow with lower concentrations of pollutants between 1720 hours and 1810 hours resulted in the movement of 1150 kg of suspended solids and 100 kg of BOD past the gauging station. The total loads of pollutants from the 131 ha catchment in 3 hours on October 20, 1975, were just over 1.2 tonnes of suspended material and just over 100 kg of BOD.

The nutrient load was also considerable. As shown in Fig. 2d the phosphate concentration tended to remain fairly constant, with the load being highly dependent on the rate of flow. This appears to be a significant result and has considerable importance for possible eutrophication of receiving waters. About 13 kg of phosphate passed the gauging station in this small flood. On the other hand the ammonia concentration fell steadily during the flood and about 11 kg of ammonia was carried.

Most of the pollutant load occurred in less than one hour. The total rainfall over the catchment for this storm was 13 mm.

Fig. 10 shows discharge, concentration and pollution load data for a storm on February 28, 1976, over Powells Creek catchment which produced about 20 mm of rain. This Figure clearly shows the effect of the first flush, which causes high concentrations of pollutants just after 1500 hours. It also shows the rapid decline of concentrations that often occurs before the discharge reaches its peak. This phenomenon is also shown at 1725 hours in Fig. 2, although there it is not as clearly visible as in Fig. 10. This rapid decline of concentration of pollutants before the occurrence of peak discharge was observed in all the larger floods sampled, and it was consistently more noticeable in Powells Creek than in Musgrave Avenue Drain. It was not observed in small floods which had peak discharges of less than about 1.5 litres/ha/s, presumably because in those cases there was more material available for a first flush than could be moved by the flood water.

Figs. 2, 5, 6, 7, and 10, which are five of the largest flood events sampled, indicate that the pollution concentration increases almost every time the discharge increases rapidly, and that whenever the discharge becomes uniform or is falling the pollutant concentration becomes quite low. This is particularly true of the concentration of suspended solids. Oxygen demand, as indicated by BOD, tends to be high in the first flush and then falls quite rapidly. The concentration of BOD increases slightly with very rapid increases in discharge, as shown at 1720 hours in Fig. 2 and at 1655 hours in Fig. 10. However the more gradual increase in discharge at 1600 hours in Fig. 10 does not affect the BOD concentration. Data from other storms indicate that once BOD concentration has decreased to a low level (say below 10 mg/l) after a first flush it only increases again when the hydrograph shows a sudden, rapid rise.

It has been observed that when small freshes occur in the storm drains very high pollution levels sometimes occur. For instance, Fig. 2 up to time 1700 hours shows the discharge and quality data which resulted from light showers over Musgrave Avenue Drain. The showers produced 1 or 2 mm of rainfall over the catchment. Whilst the amounts of suspended solids and oxygen demand resulting from these showers are not great the high concentration of pollutants and nutrients could have a considerable effect on a receiving stream which had a predominantly rural catchment, which would be the usual situation for an inland city. Under these circumstances the receiving stream would be at a very low, dry weather discharge which would be unaffected by a shower yielding

1 mm of rain. The stream would probably have insufficient diluting power to prevent oxygen levels dropping to a level which would cause fish to die. The nutrient levels would be high enough to promote rapid growth of all forms of aquatic vegetation. Small showers such as this are a frequent occurrence in any area. Other examples are shown for Musgrave Avenue Drain in Figs. 4 and 5, for Powells Creek in Fig. 8 and for Bunnerong SWC in Fig. 11. Because these small discharge, high concentration events occur frequently they could have a very significant effect on any predominantly rural stream which passes through, or close to, an urban development.

Observation of flows during floods has indicated that there are far more suspended solids than those measured in the samples. Considerable amounts of gross solids such as leaves, wood, cardboard, plastic and metal containers and sundry other large objects pass the measuring points during flood flows. These debris occur in large quantities at the same time as high concentrations of suspended solids are observed, i.e., during the "first flush" and when the discharge increases rapidly. The concentration of these large debris has not been estimated because suitable equipment for obtaining representative samples was not available.

Other parameters tend to vary in a characteristic way for all floods. As shown in Figs. 2 and 10, and mentioned earlier, the phosphate level remains approximately constant during the passage of each flood whilst the ammonia level tends to fall gradually with time. The amounts of phosphate and nitrogen carried are quite significant. As discussed above, Fig. 2 indicates that about 13 kg of phosphate was carried past the Musgrave Avenue gauging station on October 20, 1975, and Fig. 10 indicates an amount of about 4 kg was carried past the Powells Creek station on February 28, 1976. In an allegedly phosphate poor environment these amounts are very significant. The fact that the concentration remains constant during each flood is also important, especially with respect to eutrophication. Large floods usually reduce the concentration of pollutants, but in the urban environment this does not appear to be the case for phosphates. Nitrate concentration varies very little during the passage of a flood except to decrease slightly during and after peak flows. Table V shows the small range of variation of nitrate in the stormwater.

The concentration of dissolved solids tends to fall very rapidly at the beginning of each increase in runoff and remain at a low level until the flood has passed. It is of interest to note from Table IV that the concentration of dissolved solids under dry weather flow conditions is about 200 mg/l for the sandy soil basins but over three times as high for the clay soil, Powells Creek area. pH tends to fall early in the passage of a flood and to remain approximately constant. The figures shown in Table IV and V indicate that flood water is slightly acidic whilst dry weather flow is slightly alkaline.

After prolonged rain, water in all three storm drains becomes relatively pollution free. Samples have been collected in Musgrave Avenue Drain and Powells Creek after several days of continuous rain during which about 150 mm was recorded. These samples indicated maximum suspended solids and BOD concentrations of 70 mg/l and 3 mg/l respectively. Fig. 6 shows data for samples collected from Musgrave Avenue Drain after several days of rain. On this occasion the maximum suspended solids and BOD concentrations of 50 mg/l and 3 mg/l respectively were observed during a rapid rise from about 100 l/s to 1300 l/s in a few minutes. All other concentrations were also low—as low as the lowest values observed during any other flood. This finding indicates that most of the pollution is washed from urban catchments by the first 10-20 mm of rainfall, provided fairly high intensities occur, and that only minor amounts are removed by subsequent rain. This is indicated in Figs. 6 and 10 and also in Fig. 2 where the concentrations have become very low after 13 mm of rain.

In spite of the fact that concentrations become quite low after 10-20 mm of rain has fallen the annual load of pollutants carried in stormwater is very high, as will be discussed in section 6.

Oil slicks appear on the stormwater during all floods in the three drains sampled. The blue-green sheen of the slick is always clearly visible late in the passage of floods. Early in a flood it is common to observe thick, dark coloured, oily material on the surface. On occasions large amounts of oil have been observed as a small flood has receded. Major difficulties were encountered in obtaining samples which could be assumed to indicate the concentration of oil in the water due to the fact that the oil is not distributed throughout the water but floats on the surface. The only way to sample oil concentration would be to instantaneously catch every drop of water in a representative vertical section. This is not possible in flood flows without highly sophisticated equipment, which was not available. One 2-litre sample was collected from Musgrave Avenue Drain on November 17, 1975. Other data for this small fresh are shown in Table VI. The sample, which contained 0.90 gramme of oil, was collected after several millimetres of rain in the previous few hours had washed the streets. Another sample collected at the same point on February 1, 1976, contained 1.08 gramme of oil in one litre of water. Most oil would appear to originate from washings from the streets.

Some authors (e.g., Bryan, Ref. 4) have indicated significant lead concentrations in urban runoff, presumably originating from emissions from motor vehicle engines. Samples from the flood of October 20, 1975, discussed above and shown in Fig. 2 had maximum lead concentrations of 0.5 mg/l. If urban runoff water is to be used for water supply it may need treatment for removal of lead, as this is well above the safe limit for drinking purposes.

6. LOAD OF MATERIAL CARRIED

As discussed earlier Figs. 2 to 11 show that the concentration of all constituents is highest early in each storm, but that the peak rate of movement of pollutants coincides not with the maximum concentration, but approximately with the maximum discharge. Other authors (e.g., McElroy and Bell, Ref. 18) have found the same characteristics, that is, that rate of movement of pollutants is more closely related to rate of flow than to concentration. Very high concentrations of pollutants are seen in Figs. 4 and 8 but the loads of pollutants carried in these two floods are quite small. The largest flow rate from which water samples were collected is shown in Fig. 2. This flood not only has the highest instantaneous discharge, but the highest rate of movement of most pollutants and also the highest total load of pollutants of any of the floods sampled.

The storm of October 20, 1975 over Musgrave Avenue Drain catchment deposited 13 mm of rain in a period of 3 hours, as shown in Fig. 2. As discussed earlier the resulting flood carried 1150 kg of suspended solids, 100 kg of BOD, 13 kg of phosphate and 11 kg of ammonia in about 6500 m^3 of water. It is interesting to note that most of the floods shown in Figs. 2 to 11 resulted from storms in which between 2.5 and 15 mm of rain fell. The frequency of occurrence of storms of this magnitude after several dry days is quite high. For Sydney, a daily rainfall of between 2.5 and 15 mm immediately following 3 or more dry days occurs about 19 times per year. From the data given in Figs. 2 to 7 it can be estimated that light showers of this type occurring 19 times per year over the 131 ha Musgrave Avenue Drain catchment probably cause the removal of up to 15 tonnes of suspended solids, 900 kg of BOD, 150 kg of phosphate and 120 kg of ammonia per year.

Samples obtained during major storms have shown that the concentration of most pollutants falls away to very low levels after the first 10-20 mm of rain has fallen. On the average about 10 major storms occur per year in Sydney. On an annual basis, it would seem that major storm events would remove considerable amounts of pollutants. The large volume, low concentration discharges from major storms could be expected to remove at least as much material as the smaller, more frequent events. Storms which do not fit into either of the categories discussed would also contribute to the pollution loads. Hence a very conservative estimate of the annual load of pollutants removed from the 131 ha catchment by stormwater would be about two and a half times the amounts removed by small storms, or 37.5 tonnes of suspended solids, 2.25 tonnes of BOD, 375 kg of phosphate and 300 kg of ammonia.

Dry weather flow in Musgrave Avenue Drain averages 3 l/s, contributing about 80 000 m^3 per year. The product of this volume and the mean concentrations for low flows shown in Table IV would give annual low-flow pollution loads of 4.8 tonnes of suspended solids, 2.4 tonnes of BOD, 130 kg of phosphate and 135 kg of ammonia. The estimated total annual load of pollutants carried in Musgrave Avenue Drain is shown in Table VII.

7. TREATMENT OF URBAN STORMWATER

7.1 Treatment Experience Overseas

The need for treatment of urban stormwater has been amply demonstrated in Section 6 above and should not be ignored in favour of treating all urban sewage at the tertiary level. The major difficulty in treatment of urban stormwater is the huge discharges which occur for very short periods of time with long periods between flows. Economically it would be quite unreasonable to provide plant to treat stormwater at its unrestricted flow rate. Treatment of combined sewer effluent (sanitary sewage and stormwater collected in the one conduit system) is quite common overseas. Where treatment is practised overseas, storage forms an integral part of almost all the treatment works (Refs. 13, 17 and 19). The methods of treatment employed overseas are, as one would expect for the combination of sewage and stormwater, similar to those used for sewage treatment, including screens, settling tanks, sand filters, trickling filters, oxidation ponds and aeration lagoons. Some systems have large concentrated storages whilst others have the storage located throughout the system. For instance the "Chicago Tunnel and Reservoir Plan", now under construction (Ref. 19), combines a massive reservoir with large storage tunnels. The city has surface drains feeding into approximately 190 kilometres of tunnel of 3 to 12 metres diameter located 50 to 100 metres below the ground surface. Water from the conveyance/storage tunnels will be pumped to the surface reservoir from where it will be fed to the treatment plant at a fairly uniform rate.

Other U.S. cities, for instance Mt. Clemens, Michigan (Ref. 17) employ microstrainers and a system of three lagoons in series to treat overflows from combined sewers. The first lagoon serves as a storage basin and aeration pond, the second as an oxidation pond and the third as another aeration pond. The design flow-through time is just under 20 days. More than 90% of BOD and suspended solids is removed from the combined sewage at this point.

Whilst considerable effort is now being made in some areas to treat combined sewage-stormwater flows there is little evidence of separate urban stormwater being treated, except as a byproduct of some other objective. For instance stormwater held for several days in lakes and ponds which are part of the landscaping of an urban area undoubtedly undergoes considerable aeration and deposits most of its suspended load as it traverses the storage. However treatment of urban stormwater as a specific objective does not seem to be practiced anywhere.

7.2 Laboratory Experiments

In an attempt to investigate the feasibility of simple, cheap treatment of urban stormwater to remove the significant pollutants, samples of freshly collected stormwater from a number of floods were settled in Imhoff cones and the supernatant liquid examined. The stormwater samples tested were grab samples from Musgrave Avenue Drain and Powells Creek. The samples were settled and tested within four hours of collection, wherever possible. All were tested within eight hours of collection.

All samples were settled in 1 litre, 45 cm deep, Imhoff cones for 15 minutes and one hour. A few samples were settled for 4 minutes and 8 minutes and some others were settled for 2 hours and 24 hours. Supernatant liquid was drawn off at a depth of 25 cm to carry out tests for suspended solids, BOD, phosphate, ammonia and nitrate. In general it was found that settling had little or no effect on the nitrate concentration and only a small effect on ammonia concentration. However all other constituents listed above were significantly reduced, even with as little as 4 minutes settling. A very wide range of percentage removal of each constituent was achieved. Table VIII and Fig. 12 summarise the test results. They show, for instance, that initial BOD levels ranging from 2.3 mg/l to 108 mg/l were reduced by an average of 39% after 15 minutes settling. The range of concentration reduction after 15 minutes settling was from 1% to 72%. The percentage reduction of BOD was quite unrelated to the initial BOD level. Large and small reductions were achieved for both high and low initial concentrations.

Removal of total phosphate after 15 minutes settling, with initial concentrations ranging from 1.05 mg/l to 7.6 mg/l, ranged from 47% to 82% with a mean value of 62%. At one hour the mean removal of BOD was 41% and of total phosphate 71%. Suspended solids removal was by far the most spectacular. It is probable that the reduction of the concentration of the other constituents discussed above was due, in part, to the removal of the suspended solids. After 4 minutes settling the suspended solids concentrations, which ranged from 50 to 1400 mg/l, were reduced by an average of 79%. After 15 minutes settling the suspended solids were reduced by from 76% to 96%, with a mean removal of 87%.

The significant removal rates discussed above were observed at a depth of 25 cm. O'Connor and Eckenfelder (Ref. 20) have presented curves which clearly demonstrate an increase in settling velocity with depth, due to the greater degree of flocculation which has occurred. It would seem that since settling velocity increases with depth the degree of removal of material observed at 25 cm depth after 4 minutes could be expected to be reproduced at a depth of more than 4 times the experimental depth after about 15 minutes settling. The precise depth at which the 4 minute, 25 cm result would be achieved after 15 minutes would depend on the flocculating nature of the stormwater, but it could be expected to be between 1.5 and 2 metres. This extrapolation of laboratory data would need to be tested in a pilot tank before it could be used for design purposes.

7.3 Benefits of Treatment of Storm Runoff

If runoff from events such as those shown in Figs. 2 to 11 was passed through a 2 metres deep storage which provided a settling time of

15 minutes considerable benefits could be achieved. A storage of perhaps 2000 m^3 would be required for a 131 ha catchment, with outlet works arranged to permit varying rates of outflow to provide about 15 minutes settling time, irrespective of the rate of inflow. The sedimentation tanks for settling urban runoff would not need to be as large as would be required for treatment of the same rate of flow of sewage since sewage requires a much greater flow-through time. Costs involved for treatment of the urban runoff would be the initial construction costs plus the cost of dredging every few years, and perhaps 3 monthly removal of gross debris from screens at the outlet structure.

It will be assumed that a 131 ha catchment such as Musgrave Avenue Drain has a population of 5000 and that the constitution of the raw sewage from the area approximates that entering the St. Mary's Water Pollution Control Plant in Sydney. Typical concentrations of various constituents of the raw sewage and secondary effluent from the plant are shown in Table V. The mean sewage discharge for Sydney is about 140 litres/capita/day. Hence the annual loads of various pollutants in raw sewage and secondary sewage effluent from Musgrave Avenue Drain catchment would be as shown in Table IX. The stormwater loads are as shown in Table VII. Inspection of Table IX indicates that, compared with secondary sewage treatment plant effluent, storm runoff carries about six times as much suspended solids, slightly more BOD, about 20% as much phosphate and 10% as much ammonia. Rows (7) and (8) of Table IX indicate that, in terms of overall pollution abatement, benefits comparable to those obtainable from tertiary treatment of sewage can be achieved from a few minutes simple settling of storm runoff. This is based on the assumption that tertiary treatment would remove about 50% of the BOD and suspended solids from the secondary sewage effluent. Tertiary treatment of sewage would have a larger effect on the total BOD load than settling of stormwater but a much smaller effect on the suspended solids and little or no effect on the nutrient loads. Comparison of rows (6), (7) and (9) of Table IX indicates that it is probably not worth providing tertiary treatment of sewage without treating storm runoff.

The results shown in Table IX are based on the assumption that the population of the 131 ha catchment is 5000, or 38 per ha. If the population density was lower, the load of pollutants carried in sewage would be less but that carried by the stormwater would only be slightly affected. Hence for a lower population density, treatment of urban runoff would provide greater advantages relative to tertiary treatment of sewage than is shown in Table IX.

The limited resources available for control of pollution and the results outlined above indicate that serious consideration should be given to the incorporation of simple treatment of storm runoff in the overall strategy of water pollution control in urban areas. Treatment of urban storm runoff may have little effect on the internal environment of a city but could make a considerable contribution to the quality of receiving waters downstream of the urban area.

8. CONCLUSION

Measurement of quality parameters of urban runoff in Sydney has shown that significant pollution and nutrient loads are carried in surface waters emanating from completely sewered areas. As observed in other urban areas the concentration of pollutants tends to increase rapidly at the beginning of flood flow and then to decrease as the flood progresses. During the early part of each flood the concentration of suspended solids is usually higher than for raw sewage and the BOD is usually between 20% and 50% of that of raw sewage. This early stormwater has significantly higher concentrations of pollution materials than secondary sewage effluent. During the later stages of urban floods the pollution concentrations usually fall to about the same level as for secondary sewage effluent.

The concentration of nutrients tends to remain constant or to fall slowly during the passage of a flood. Ammonia behaves similarly to BOD but phosphate concentration tends to remain approximately constant. This constant concentration of phosphate is superimposed by fairly high peak values which occur each time the discharge increases. The nutrient concentrations are usually in the range of 5-40% of those observed in secondary sewage effluent.

In the long term the total load of pollutants carried in storm runoff is considerably higher than in secondary treatment plant effluent from the same area. The shock load of polluting material carried in stormwater can be even more important, especially for streams near inland cities. Floods which resulted from 13 mm and 7.5 mm rainfall on a 131 ha catchment carried respectively 1150 kg and 800 kg of suspended solids, 100 kg and 70 kg of BOD, 13 kg and 5 kg of phosphate and 11 kg and 4 kg of ammonia. Such storms over rural catchments would probably produce no significant runoff and hence the above loads of material carried from an urban area by these storms would seriously degrade the receiving stream which would have little or no ability to dilute the urban runoff.

Simple laboratory tests were made to examine the possible benefits obtainable from treatment of urban runoff. The tests showed that for the Sydney catchments simple settling of the urban runoff could reduce the pollution load contributed to receiving waters by an amount approximately equal to the reduction that could be obtained by tertiary treatment of the secondary sewage effluent from the same area. It was also shown that tertiary treatment of secondary sewage effluent without treating stormwater would produce very little reduction in the overall pollution load carried in water flowing from an urban area.

The cost of treating storm runoff by simple settling would probably be much less than the cost of tertiary treatment of secondary sewage effluent from the same area.

9. ACKNOWLEDGEMENTS

The author is indebted to Mr. H. H. Rups for performing the oil and lead concentration tests and for other helpful advice concerning testing of water samples, and to the Secretary, Metropolitan Water, Sewerage and Drainage Board, Sydney for supplying sewage effluent data shown in Table V.

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TABLE I QUALITY DATA FROM OTHER STUDIES

Reference	(24)	(4)	(23)	(6)	(5)	(11)	(26)	(15)	(10)	(2)	(25)	(3)
Parameter	mean	mean	range	mean	range	range	mean	mean	mean	mean	mean	mean
Suspended solids mg/1	227	3930		1360		110—930	2730	280	26	360	210	1280
Dissolved solids mg/1									208	411		
Ammonia nitrogen mg/1								0.45			0.6	0.48
Nitrate nitrogen mg/1				0.6			1.9	0.60	16.4	6.2	0.4	
Phosphate as P mg/1	1.1	0.55		2.9		0.7—8.1	0.6	0.98	0.22		0.8	2.9
BOD_5 mg/1	17	31	6.1—223	29		4—220	14.5			6.9	19	
DO mg/1												
pH	7.5								8.19		7.5	
Faecal coliforms (MPN/100 ml)	10^4				7.4×10^3—7.5×10^5	5×10^3—2.9×10^5	3×10^4				1.1×10^4	8.2×10^4
Total coliforms (MPN/100 ml)		2.5×10^5			1.2×10^4—34×10^6	2.3×10^4—45×10^6					5.8×10^4	1.2×10^6

TABLE II CHARACTERISTICS OF DRAINAGE AREAS

	Musgrave Avenue Drain	Powells Creek	Bunnerong SWC
Area (ha)	131	231	55
Maximum elevation difference (m)	70	40	20
Mean slope (%)	5.0	2.0	1.5
Mean annual rainfall (mm)	1150	990	1130
Land use	Residential—individual dwelling units set in about 0.04 ha, 10% of dwellings in multi unit blocks	Residential—primarily individual dwellings set in about 0.06 ha	Residential—individual units set in about 0.05 ha, some multi unit blocks, shopping centre occupies 20% of area
Population (est.)	5000	6500	2000
Soil type	Sand	Clay	Sand
Area of parkland (ha)	27	3	0

TABLE III TESTS MADE ON STORMWATER

Parameter	Name of Test	Reference
Suspended solids	Photometric method for water and wastewater	(16)
Turbidity	Absorptometric method for water	(12)
BOD_5	Winkler-azide titration	(1), p.477
Dissolved oxygen	Winkler-azide titration	(1), p.477
pH	Direct reading meter	
Phosphate	Persulphate digestion method	(1), p.526
Ammonia	Nesslers method	(1), p.226
Specific conductance		(1), p.458
Total coliforms	MPN technique with McConkey broth	(8)
E. coli	Eijkman test	(8)
Hardness	EDTA titration	(1), p.84
Alkalinity	Phenolphthalein titration	(1), p.52
Chloride	Silver nitrate titration (silver nitrate substituted for mercuric nitrate)	(1), p.97
Silica	Heteropoly blue method	(1), p.306
Sulphate	Turbimetric method	(1), p.334
Oil	Solvent extraction	(1), p.254
Lead	Atomic absorption spectrophotometric method	(1), p.211

TABLE IV DRY WEATHER FLOW QUALITY DATA

Parameter	Concentration (mg/l except pH, coliforms and turbidity)								
	Musgrave Avenue Drain			Powells Creek			Bunnerong SWC		
	Number of samples	Mean	Range	Number of samples	Mean	Range	Number of samples	Mean	Range
Suspended solids	10	59	0—295	4	85	10—240	6	19	8—115
Dissolved solids	8	250	210—330	4	690	600—840	5	184	90—220
Ammonia Nitrogen	10	1.7	0.3—4.9	4	1.14	0.4—2.1	6	0.88	0.32—2.6
Nitrate Nitrogen	9	1.5	1.0—2.5	2	0.98	—	6	0.39	0.12—1.05
Nitrite Nitrogen	8	0.21	0—0.76	2	0.14	0.13—0.16	5	0.02	0—0.03
Phosphate as P	9	1.6	0.8—3.2	4	2.2	0.7—4.9	5	1.35	0.8—2.0
BOD_5	10	31	4.2—135	4	7.6	3.3—12	6	19	5.9—63
pH	10	7.42	6.71—7.83	3	7.51	7.22—7.70	6	7.34	6.92—7.90
Total coliforms (MPN/100 ml)	8	5.3×10^6	0.5×10^6— 18×10^6	3	4×10^6	5×10^4— 11×10^6	5	3.3×10^6	0.2×10^6— 16×10^6
Hardness (total)	8	100	84—136	2	158	154—162	6	81	56—98
Alkalinity	4	50	32—62	2	86	85—88	4	58	40—76
Chloride	8	38	29—59	2	186	136—237	6	34	15—41
Sulphate	7	45	28—60	2	99	82—115	6	29	20—47
Silica	7	6.6	5.0—8.4	2	8.2	6.4—10.0	6	7.0	4.2—9.5
Turbidity (FTU)	10	66	9—250	2	132	100—165	6	27	8—52

TABLE V COMPARISON OF QUALITY OF URBAN FLOOD FLOWS AND SEWAGE EFFLUENT

Parameter	Concentration (mg/l except pH and coliforms)										
	Musgrave Avenue Drain			Powells Creek			Bunnerong SWC			St. Marys Water Pollution Control Plant	
	Number of samples	Mean	Range	Number of samples	Mean	Range	Number of samples	Mean	Range	Raw sewage effluent	Secondary sewage effluent
Suspended solids	69	269	12—940	31	236	30—1400	11	275	95—520	270	28
Dissolved solids	57	120	26—390	31	118	30—650	11	137	40—255	570	530
Ammonia Nitrogen	63	2.39	0.35—13.3	31	1.92	0.37—14.0	11	2.75	1.2—4.1	41	22
Nitrate Nitrogen	23	0.78	0.14—1.9	4	0.96	0.51—1.60	6	0.61	0.22—0.86	—	4
Phosphate as P	41	2.95	0.75—7.6	29	1.60	0.63—5.1	6	2.1	0.63—4.3	10.5	10
BOD_5	66	30	1.3—145	31	18	2.5—71	11	28	5.8—62	265	16
DO	22	5.1	0.3—7.9	6	3.1	0.5—5.0				0.6	3.5
pH	44	6.78	5.80—7.55	19	6.98	6.61—7.52	11	6.47	6.13—6.81	7.4	7.2
Faecal coliforms (MPN/100 ml)	12	41×10^4	0— 120×10^4	7	41×10^4	9×10^4— 93×10^4	2	6.5×10^4	4×10^4— 9×10^4	20×10^6	1180
Total coliforms (MPN/100 ml)	15	5.6×10^6	40×10^4— 23×10^6	7	2.2×10^6	23×10^4— 9.3×10^6	3	2.0×10^6	23×10^4— 4.6×10^6	—	—

TABLE VI INCOMPLETE FLOOD DATA—MUSGRAVE AVENUE DRAIN AND BUNNERONG SWC

	Musgrave Avenue Drain																		Bunnerong SWC		
Date	1-9-75	1-9-75	1-9-75	23-9-75	23-9-75	23-9-75	28-9-75	28-9-75	28-9-75	28-9-75	28-9-75	17-11-75	17-11-75	17-11-75	17-11-75	11-5-76	11-5-76	11-5-76	16-9-75	16-9-75	16-9-75
Time	0845	0850	0855	1738	1746	1905	0758	0804	0820	0828	0840	0430	0447	0515	0524	0612	0625	0855	1934	1942	1949
Suspended solids (mg/l)	760	440	420	230	86	25	28	55	18	23	21	0	8	0	8	370	940	220	470	520	400
Dissolved solids (mg/l)	152	90	105	67	71	79	177	124	43	39	38	73	43	53	53	208			170	115	120
Ammonia Nitrogen (mg/l)	8.3	3.0	4.1	1.8	1.7	1.3	1.4	1.8	1.0	1.1	0.9	1.1	0.7	0.7	0.7	4.5	3.4	2.5	3.1	2.5	2.6
Nitrate Nitrogen (mg/l)	0.14	0.53	0.63	0.67	0.67	0.67										1.08			0.76	0.22	0.47
Phosphate as P (mg/l)	3.8	5.1	3.8	1.0	1.2	0.6										3.7	4.4	2.4	1.3	0.6	4.3
BOD_5 (mg/l)	65	49	42	20	14	6.0	15	17	8	8	11	14	16	6	9	100	83	19	30	62	46
pH	7.30	7.30	7.10	7.04	7.33		6.88	6.91	7.00	7.00	7.00	7.18	7.67	7.38	7.70				6.66	6.69	6.81
Faecal coliforms (MPN/100 ml)				20×10^4	20×10^4	93×10^4															
Total coliforms (MPN/100 ml)	13×10^6		23×10^6	0.75×10^6	11×10^6	0.93×10^6													1.1×10^6		
Discharge (l/s)	450	310	450	260	70	55	26	70	360	260	95	26	172	46	204	26	31	31	19	22	10

TABLE VII ANNUAL POLLUTANT LOADS CARRIED IN COMPONENT DISCHARGES—MUSGRAVE AVENUE DRAIN

	BOD_5 (kg)	Suspended Solids (kg)	Phosphate as P (kg)	Ammonia nitrogen (kg)
Floods resulting from 2.5 to 15 mm of rainfall	900	15 000	150	120
Major floods	1 350	22 500	225	180
Dry weather flow	2 400	4 800	130	135
Total	4 650	42 300	505	435
Total in kg/ha/yr	35.5	323	3.85	3.32

TABLE VIII REDUCTION OF CONCENTRATION OF VARIOUS PARAMETERS BY SIMPLE SETTLING FOR PERIODS SHOWN

Constituent	Range of initial concentrations mg/1	Mean initial concentration mg/1	Mean reduction of concentration %			
			4 mins settling	8 mins settling	15 mins settling	1 hour settling
Suspended Solids	50—1400	430	79	84	87	90
BOD_5	2.3—800	49	34	36	39	41
Phosphate	1.05—7.6	4.15	57	61	62	69
Ammonia	1.5—14.0	3.94	18	20	22	24

TABLE IX ESTIMATED ANNUAL LOAD OF VARIOUS CONSTITUENTS OF WASTEWATER FROM MUSGRAVE AVENUE DRAIN CATCHMENT

		BOD_5 (kg)	Suspended Solids (kg)	Phosphate as P (kg)	Ammonia nitrogen (kg)
Raw sewage	(1)	68 000	69 000	2 700	10 500
Secondary sewage effluent	(2)	4 100	7 200	2 500	5 600
Tertiary sewage effluent (est.)	(3)	2 050	3 600	2 500	5 600
Urban runoff	(4)	4 650	42 300	500	430
Urban runoff settled for 15 minutes in a 2 m deep tank	(5)	3 070	8 900	215	350
Secondary sewage effluent plus urban runoff	(6)	8 750	49 500	3 000	6 030
Tertiary sewage effluent plus urban runoff	(7)	6 700	45 900	3 000	6 030
Secondary sewage effluent plus settled urban runoff	(8)	7 170	16 100	2 715	5 950
Tertiary sewage effluent plus settled urban runoff	(9)	5 120	12 500	2 715	5 950

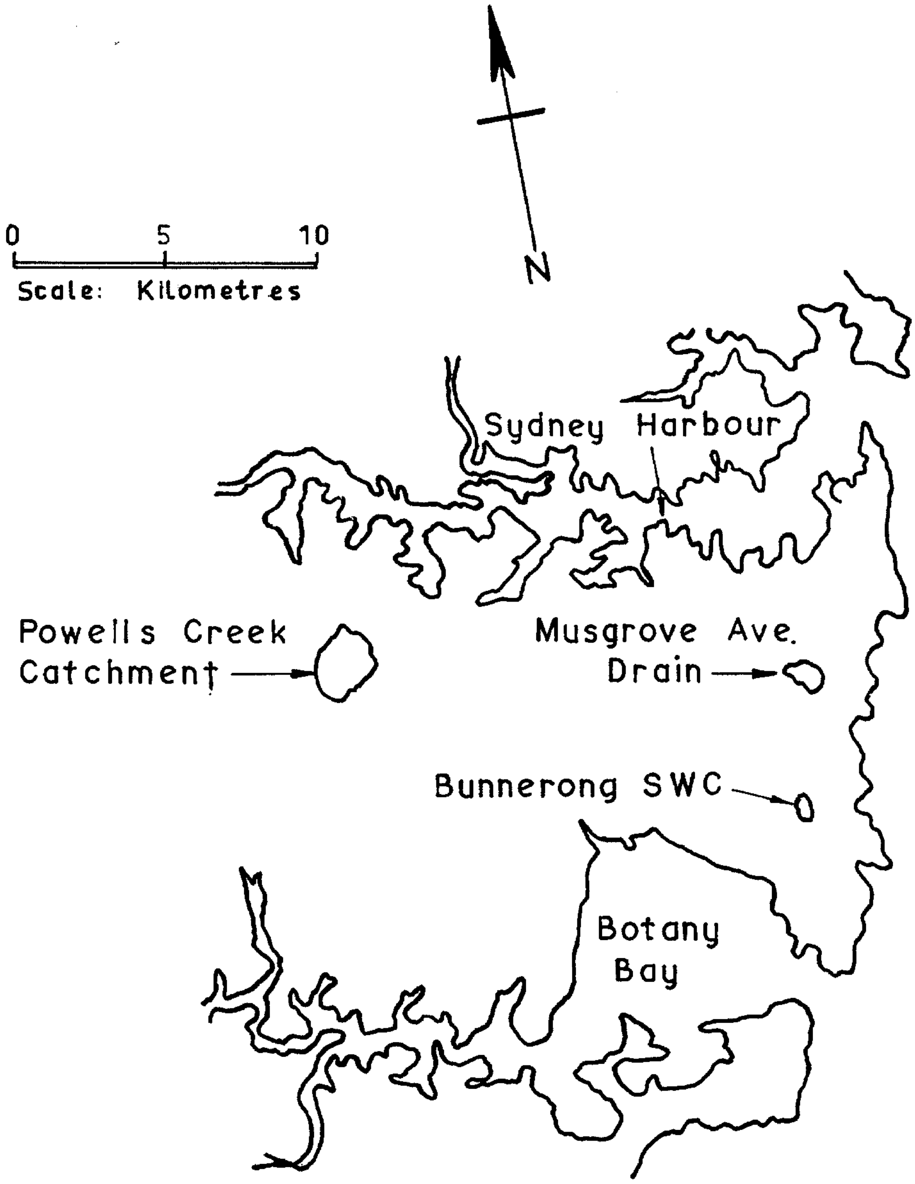

Figure 1: Location of catchments in
Sydney urban area.

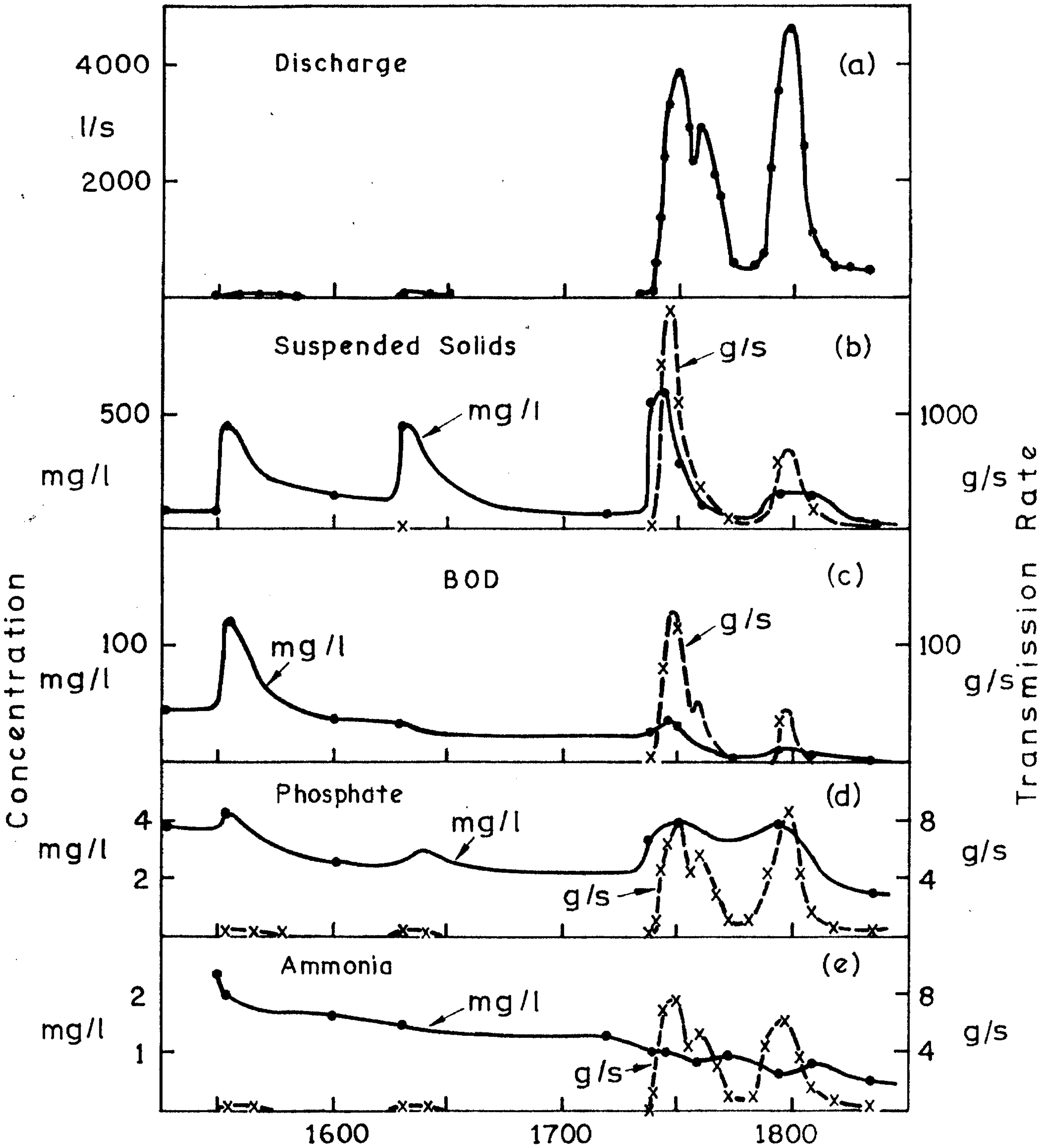

Figure 2: Musgrave Drain October 20, 1975
Concentration (mg/l) and transmission rate (grammes/s) of pollution and nutrient indicators.

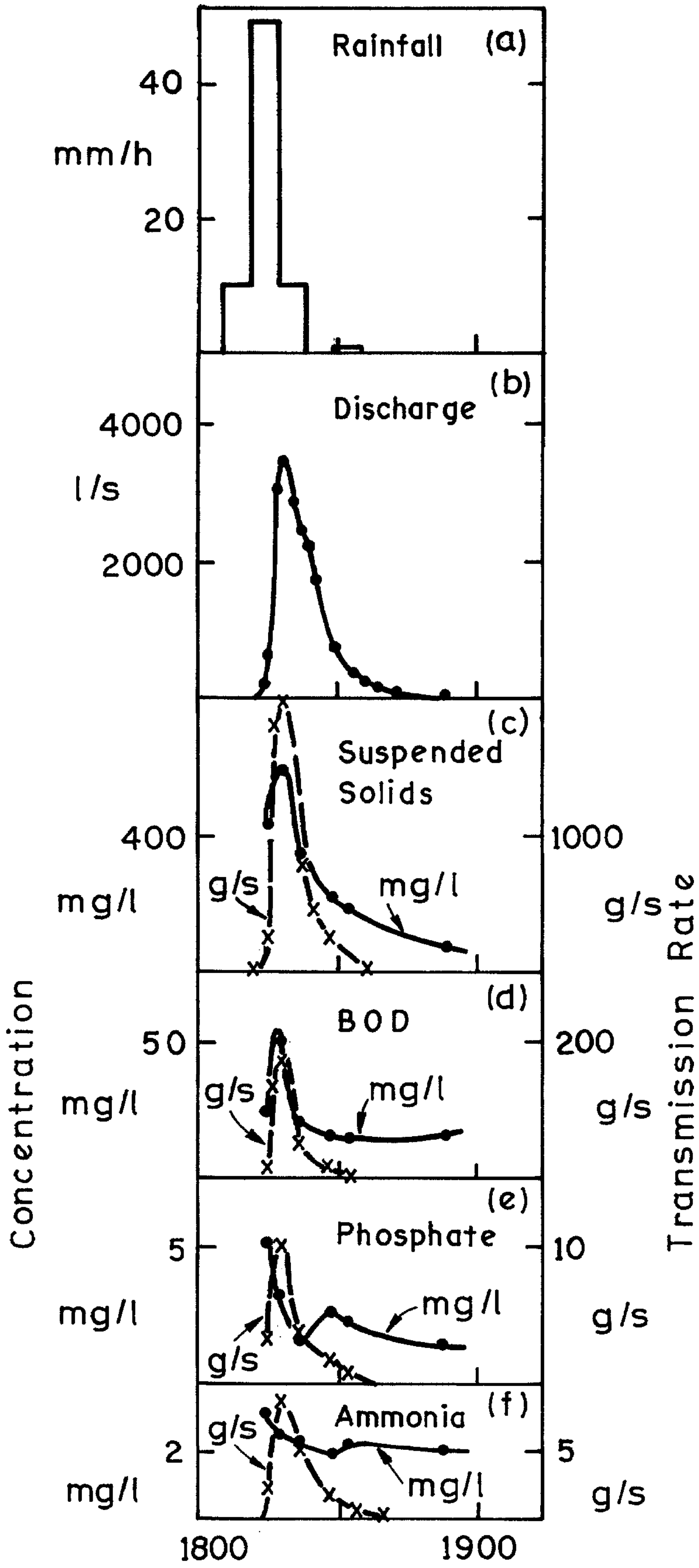

Figure 3: Musgrave Ave. Drain November 23, 1975. Concentration (mg/l) and transmission rate (grammes/s) of pollution and nutrient indicators.

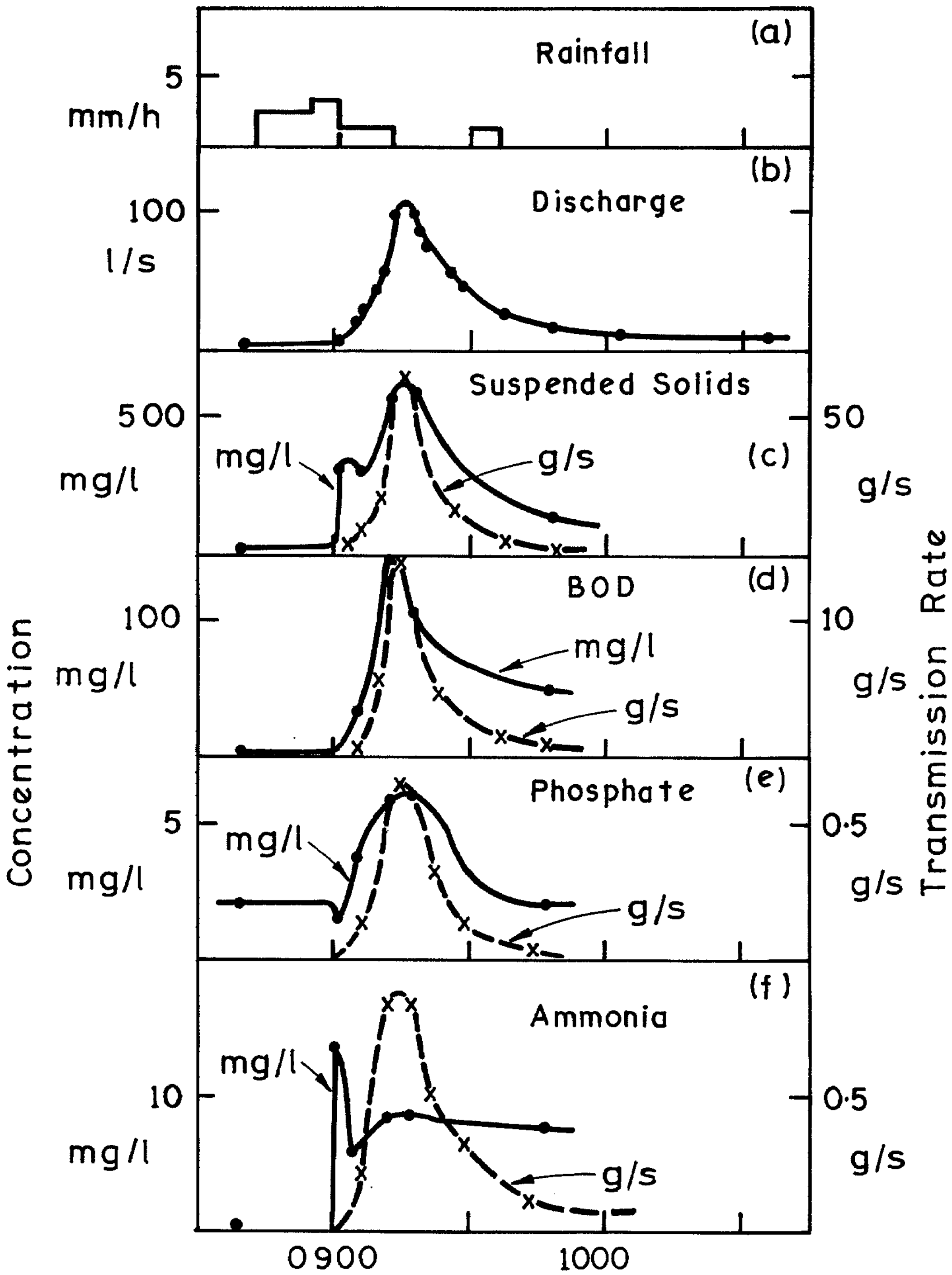

Figure 4: Musgrave Ave. Drain December 4, 1975. Concentration (mg/l) and transmission rate (grammes/s) of pollution and nutrient indicators.

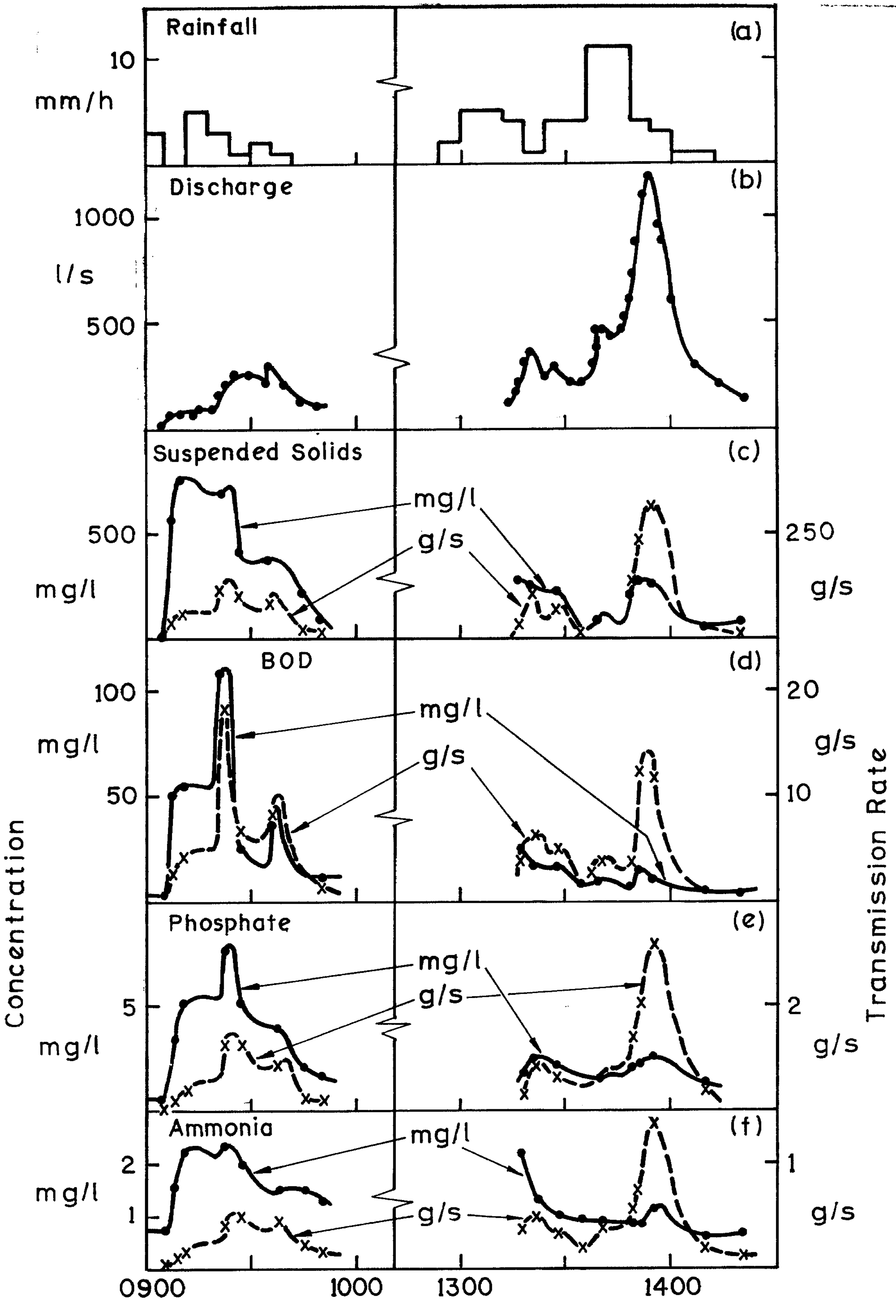

Figure 5: Musgrave Ave. Drain, December 19, 1975. Concentration (mg/l) and transmission rate (grammes/s) of pollution and nutrient indicators.

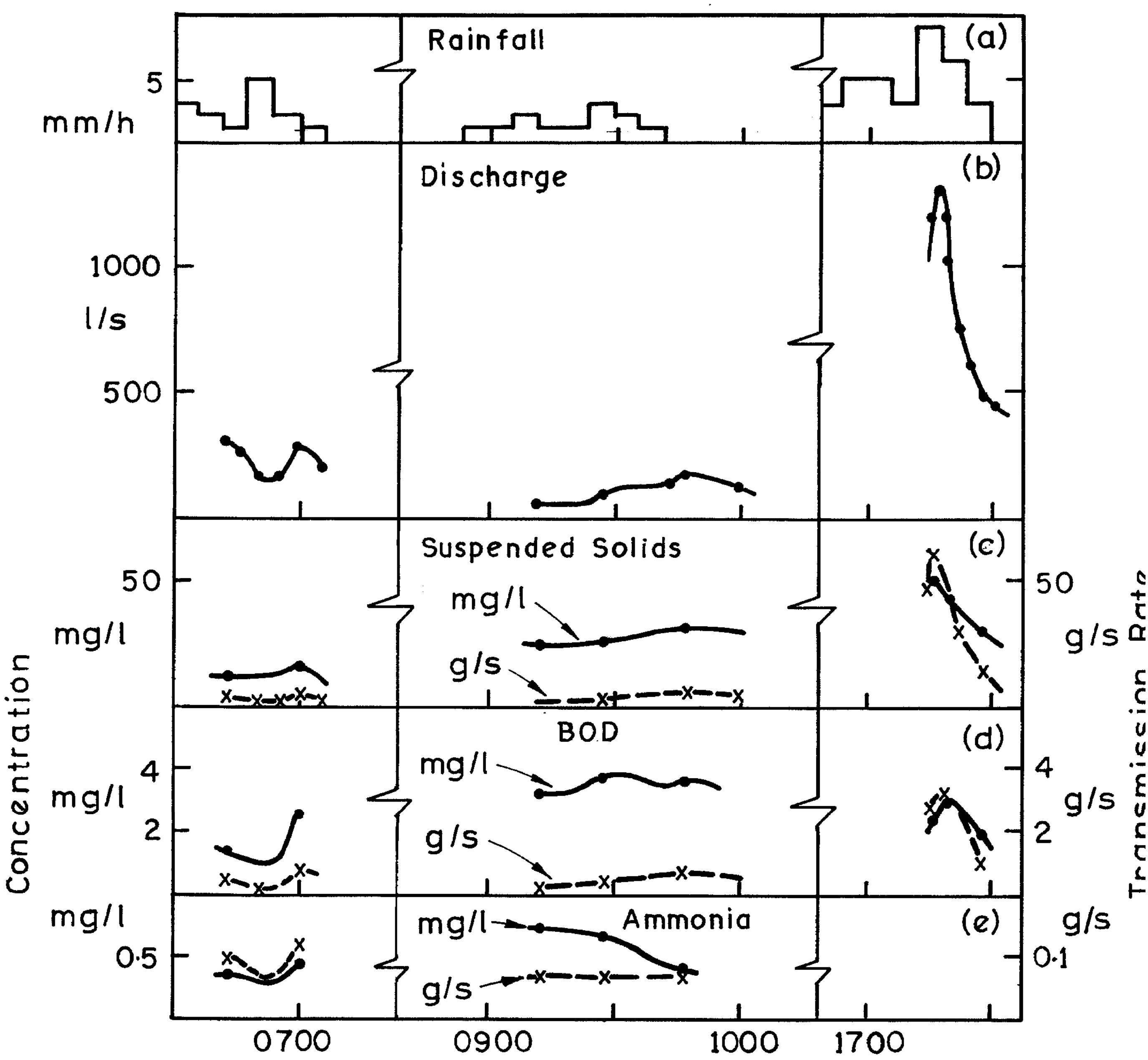

Figure 6: Musgrave Ave. January 22, 1976.
Concentration (mg/l) and transmission rate (grammes/s) of pollution and nutrient indicators.

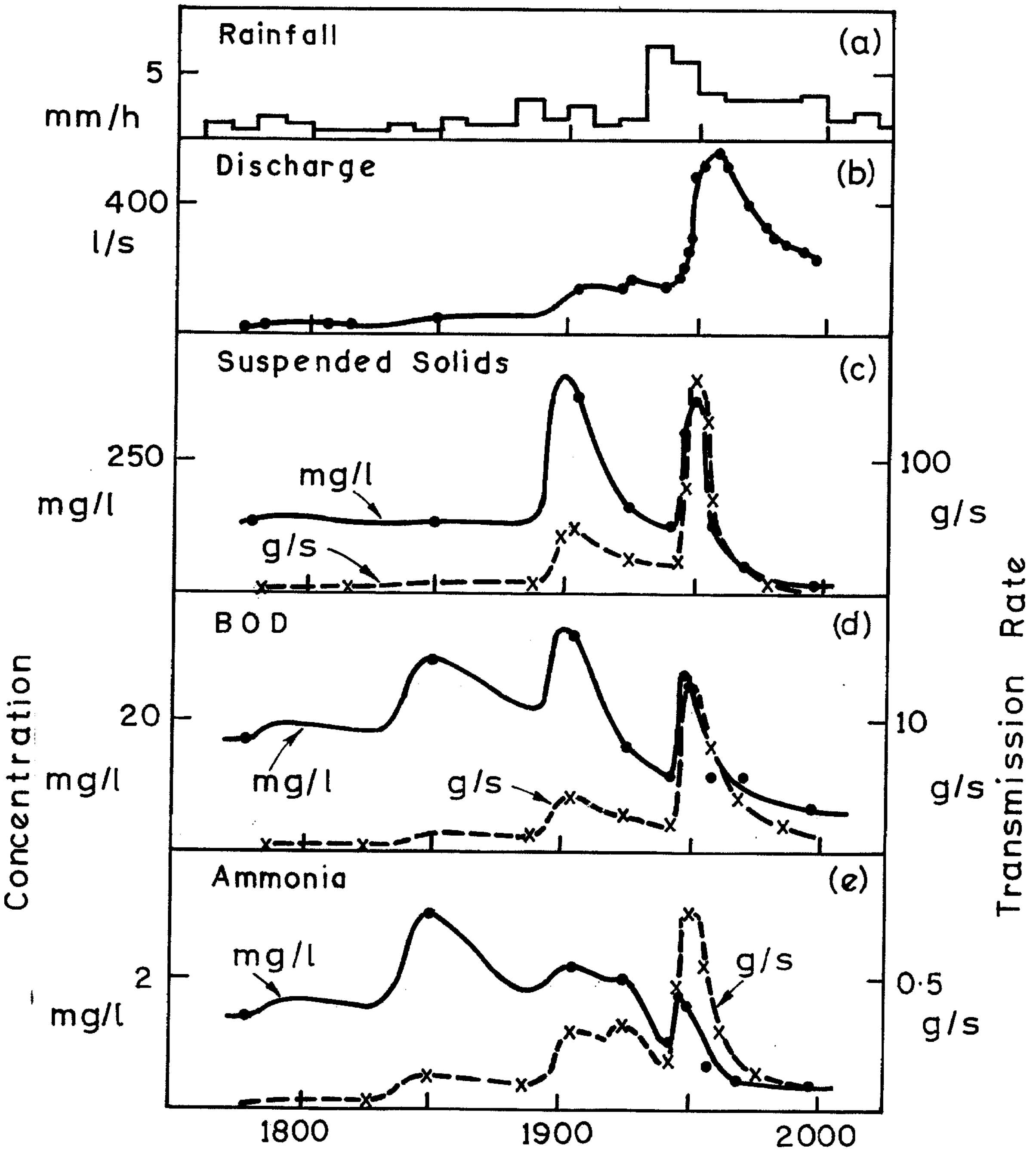

Figure 7: Musgrave Ave. Drain Februay 1, 1976. Concentration (mg/l) and transmission rate (grammes/s) of pollution and nutrient indicators.

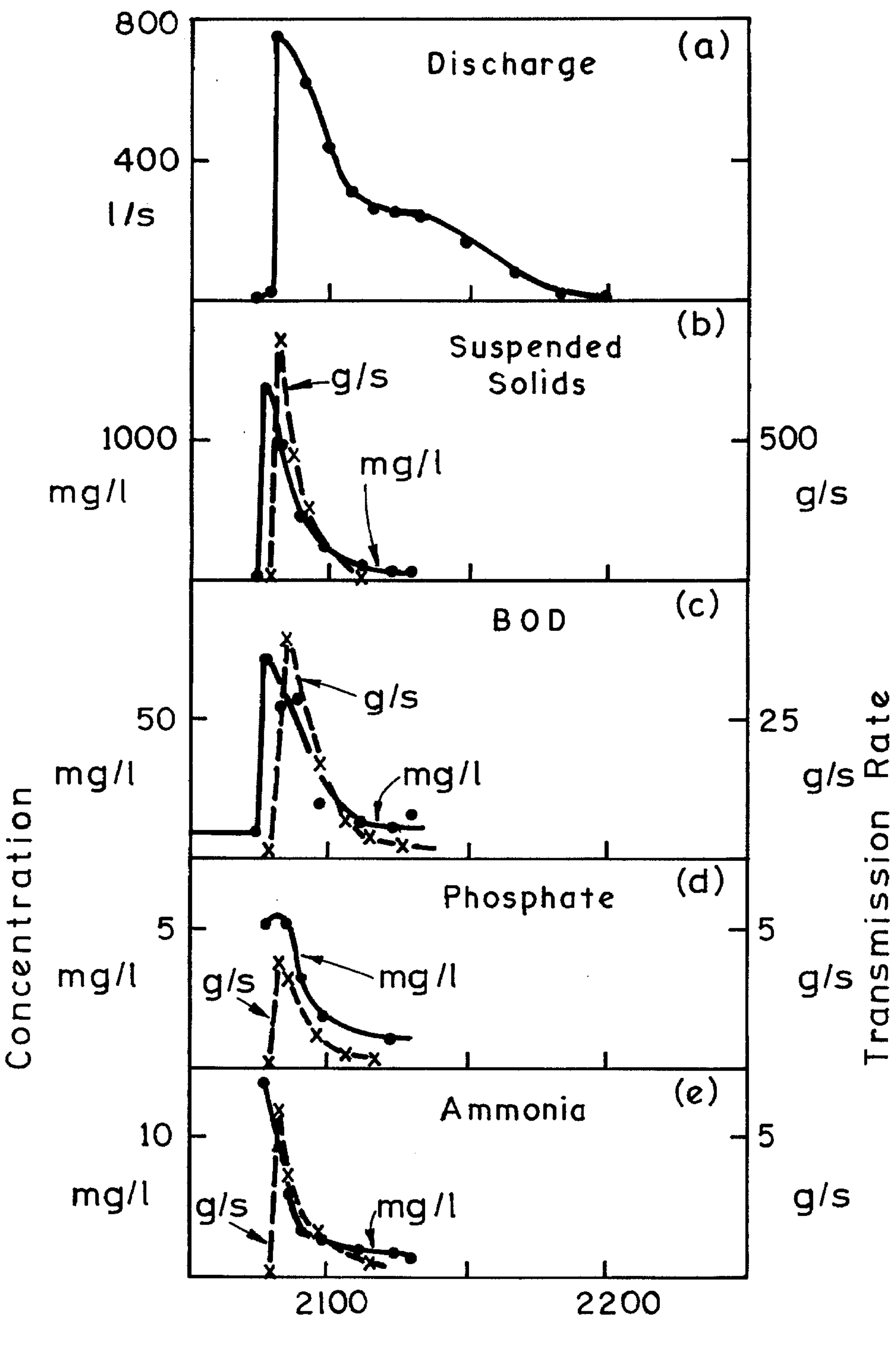

Figure 8: Powell's Creek. January 5, 1976. Concentration (mg/l) and transmission rate (grammes/s) of pollution and nutrient indicators.

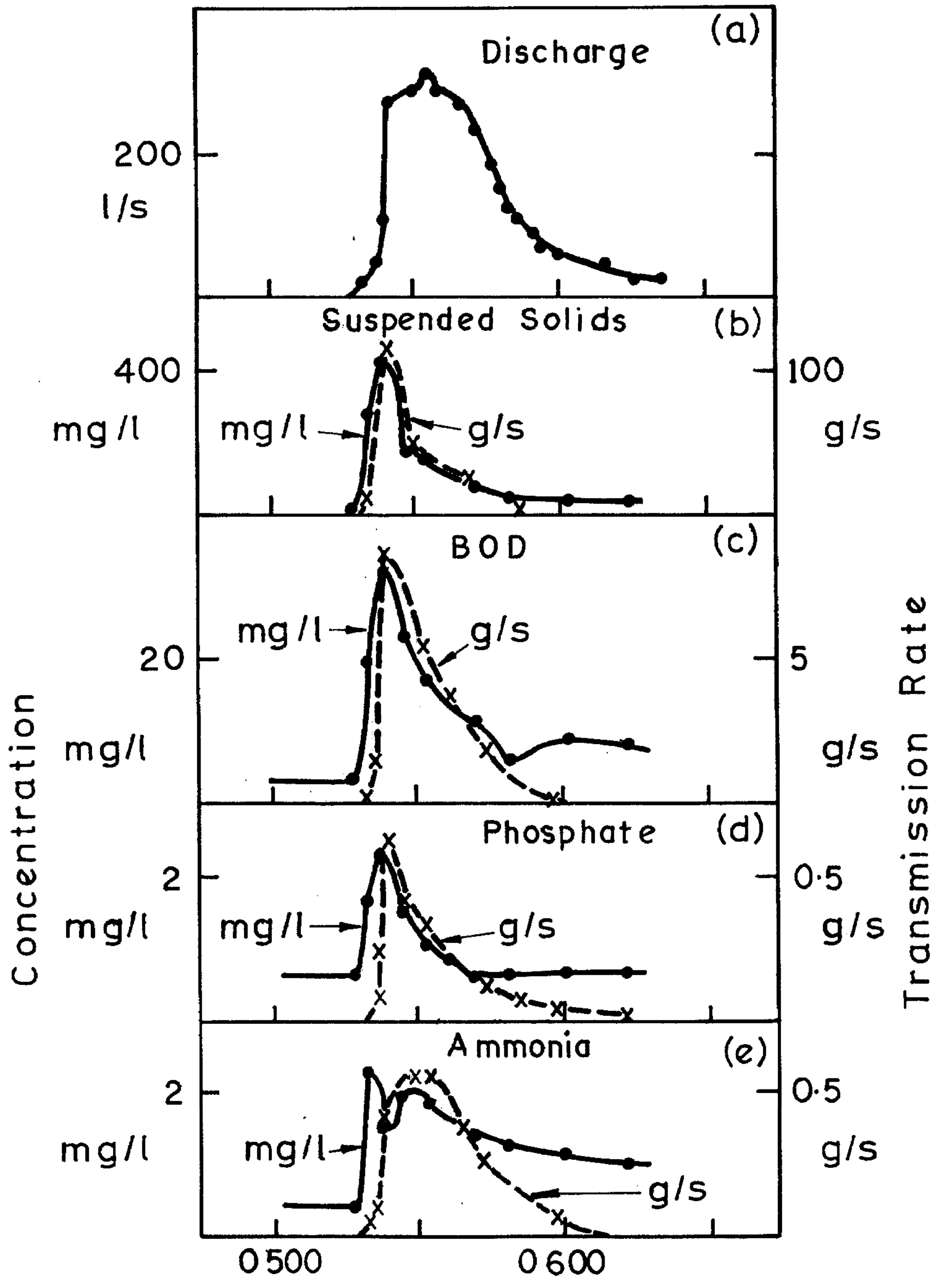

Figure 9: Powell's Creek, February 6, 1976. Concenration (mg/l) and transmission rate (grammes/s) of pollution and nutrient indicators.

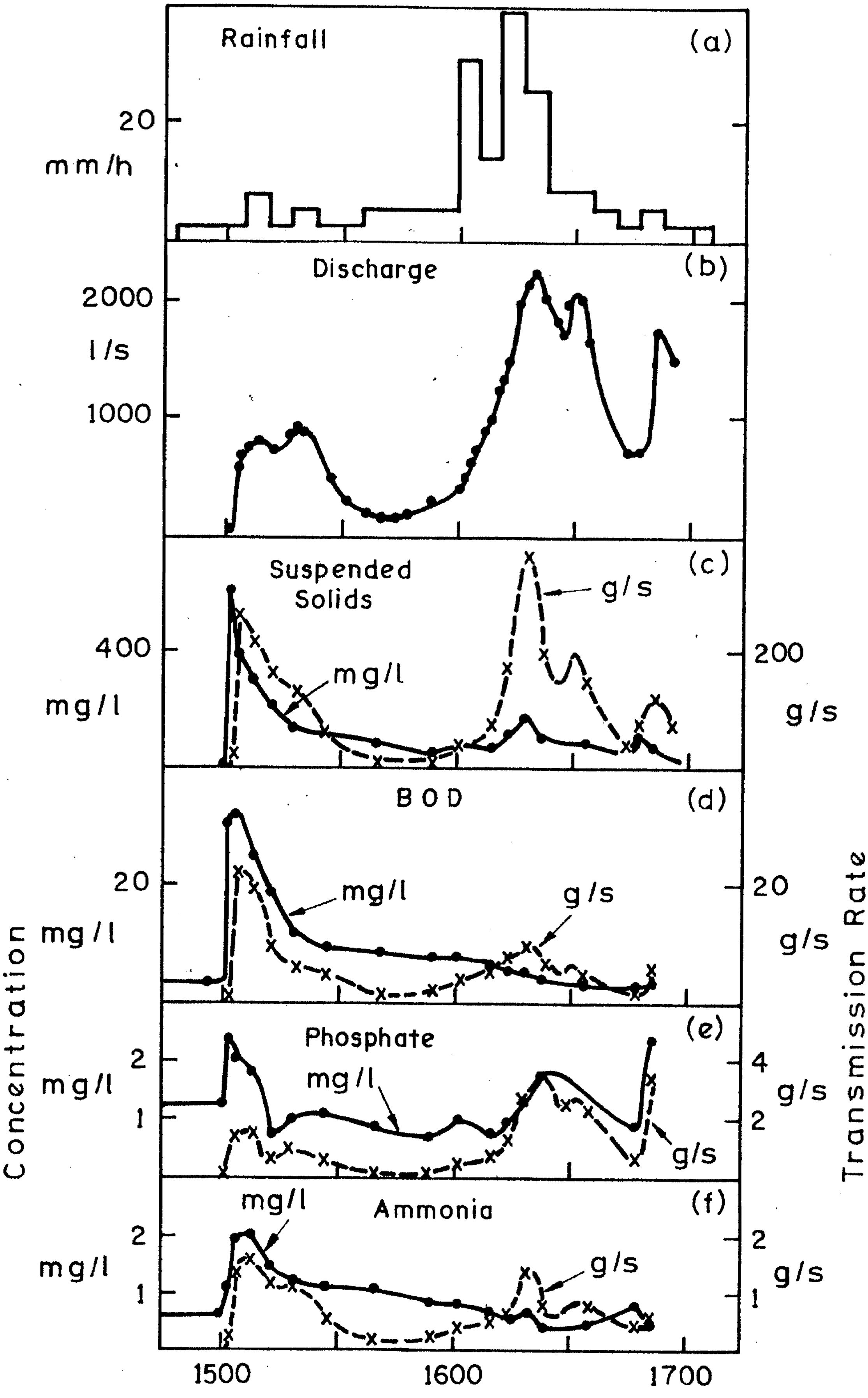

Figure 10: Powell's Creek February 28, 1976. Concentration (mg/l) and transmission rate (grammes/s) of pollution and nutrient indicators.

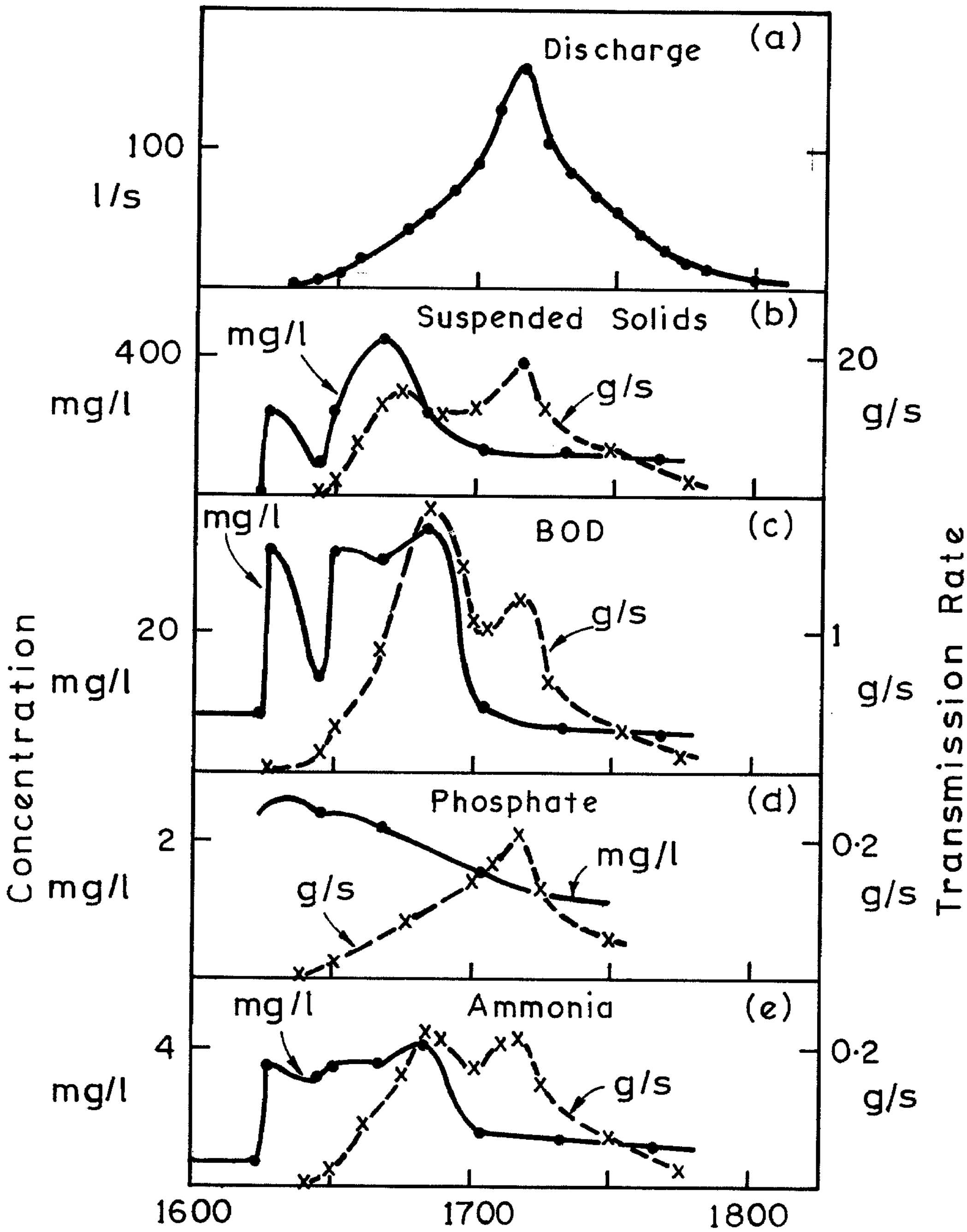

Figure 11: Bunnerong S.W.C. October 10, 1975. Concentration (mg/l) and transmission rate (grammes/s) of pollution and nutrient indicators.

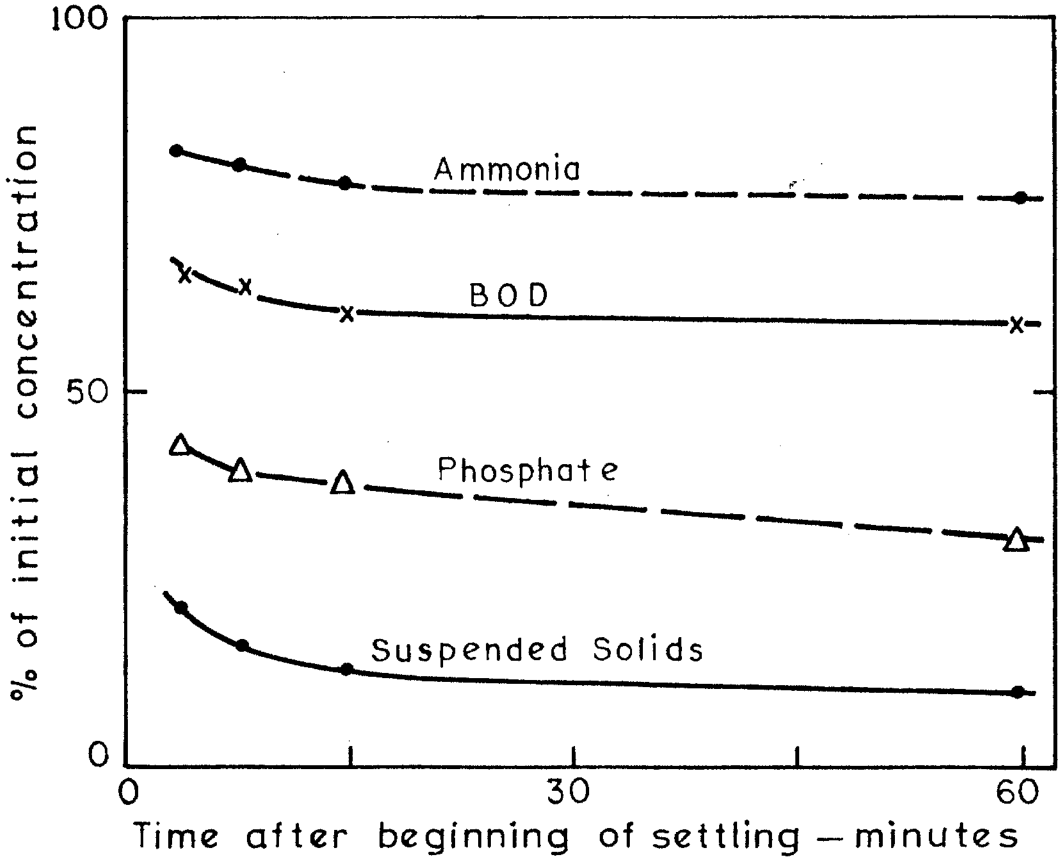

Figure 12: Average reduction of concentration of pollutants and nutrients by settling stormwater.