Water governance at Loch Leven, Scotland.

Linda May, Centre for Ecology & Hydrology

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Introduction

Background

Loch Leven has supplied water to downstream industry since the early 1700s. The water is used as a source of power generation, for cooling, or in the manufacturing processes themselves (Munro, 1994). By the 1820s, there were 40 such industries downstream of the loch. These included corn mills, sawmills, paper mills, textile mills and bleaching fields. As these industries expanded, water shortages started to occur, especially during the summer months. It was, therefore, concluded that the water discharged from the loch needed to be managed more effectively to support the growth of these industries, and the jobs and income that they provided for the local community.

Several options were explored. Local industrialists preferred the option of raising the level of the loch and, thus, its storage capacity. In contrast, local landowners, whose land would be flooded if the level was increased, strongly supported the alternative option of lowering the level of the loch and building sluice gates to manage the rate of discharge (Munro, 1994). It was argued that the latter option would have additional benefits, including new areas of highly productive farmland around the margins of the loch and a mechanism for controlling downstream flooding. This was approved "for recovering, draining and preserving certain lands in the counties of Fife and Kinross; and for better supplying with water the mills, Manufactories and Bleach fields and other works situated on or near the River Leven in the said county of Fife" by an Act of Parliament (Parliament, 1827). By implementing the agreed building works, it was hoped that evaporative losses from the loch would be reduced and more land would be provided for agricultural use to meet the increasing demand for food from growing urban populations. Mill owners and industrialists downstream were persuaded to help finance the scheme by convincing them that they would benefit from a more regular water flow all year round.

Figure 1 Sluice gates on the outflow from Loch Leven. (Photo: Linda May)

Action

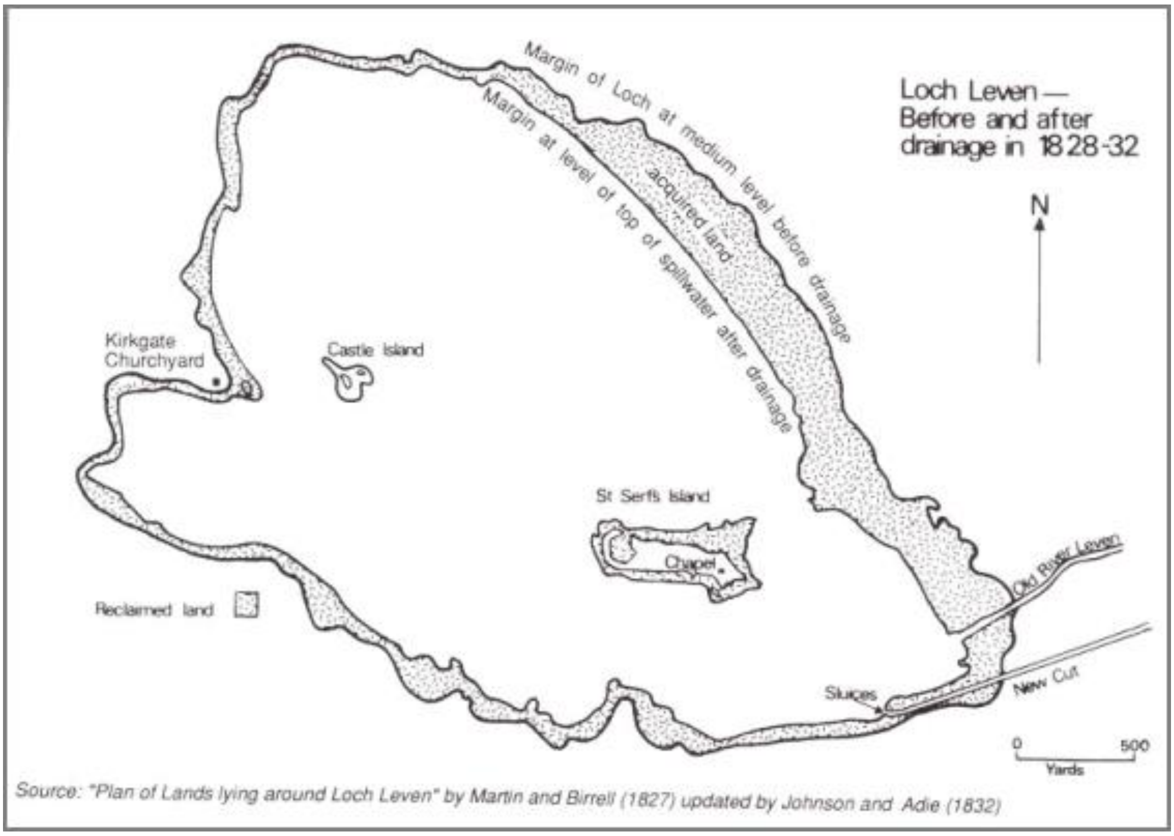
Building and land drainage works began in 1831. These lowered the level of the loch, installed sluice gates on the outflow and straightened the outflow over the first 5.2 km of its length (to form the 'Cut'). Five sluice gates were installed, opened and closed by a mechanical device with the number of screw turns being recorded to calculate the change in the size of the opening; later this was measured using a Vernier gauge. Under normal conditions, only four of the gates are used to discharge water. The centre gate remains shut and a measurement of flow is made behind it. A spillway was constructed at a level of 1.37m above the sluice gate sills.

By 1830, the water level had been lowered by about 1.5m (Morgan, 1970). This caused the surface area and mean depth to be reduced by 25% and 30%, respectively (Kirby, 1974; Smith, 1966). From 1830 onwards, the level of the loch was managed to ensure that it was full to capacity (i.e. water level ca. 107.3 m.a.o.d.) by late spring. After that, its rate of discharge was controlled to ensure that the level of the loch fell by about 0.18 m per month over the summer period (May & Carvalho, 2010).

The total cost of these 'improvements' was about £40,000 at the time, a final figure that was more than double the original estimate (Munro, 1994). This is equivalent to a present day value of about £4.2M. Although many of the mills and industries have now closed, the sluice gates (Figure 1) still regulate the outflow from Loch Leven. As such, the loch is, effectively, a reservoir that provides a regular water supply of about 5,000 m^3s^{-1} to downstream industrial users. The discharge from the loch and the loch level are managed by the River Leven Trust.

Impact

The drainage works described above successfully met their primary aim of providing a more stable and reliable water supply to downstream users (Sargent & Ledger, 1992). However, the secondary aim of increasing the area of land available for farming around the margins of the loch was only partially met. A strip of new land, up to 500 m wide, was created around the shoreline of the loch, four islands were enlarged and three new islands were created (Figure 2). However, these works had been expected to provide an extra 440 hectares of good quality land (Committee for the Society for the Sons and Daughters of the Clergy, 1831); in reality, only 265 hectares of poor quality land was reclaimed. In addition, the associated economic benefits of the engineering works were found to be 75% lower than anticipated (Munro, 1994). Another problem was that the management of the outflow proved more difficult than expected and, initially, the incidence of downstream flooding increased. This led to several claims for compensation payments from farmers whose land had been flooded (Munro, 1994). In the longer term, however, the water stored in the loch was controlled successfully and provided higher and more stable summer flows in the River Leven to support the growth of the mills. The work was completed by 1850, and the sluice gates remain in operation today with discharge data being collected every day, since then.



Source: "Plan of Lands lying around Loch Leven" by Martin and Birrell (1827) updated by Johnson and Adie (1832)

Figure 2 Map of Loch Leven showing the shoreline before and after the water level was lowered in 1830.

Changes in the depth and size of the loch affected its ecology. In particular, the sluice gates prevented migratory fish such as salmon, sea trout and charr entering the loch via its outflow. In addition, the lowering of the water level adversely affected the habitat and food supply of the resident fish community, reducing the value of the fishery by about 33% (Fleming, 1836). However, the associated 25% increase in the flushing rate of the loch may have helped to reduce the likelihood of algal blooms, when the loch started to become a more nutrient rich system in later years.

Sluice gate management, annual water balance and estimation of discharge

Once the sluice gates were in place, the level of the loch was no longer determined by local rainfall; instead it was controlled by the demands of downstream industry. This situation continues to the present day, with water flow from Loch Leven to the River Leven being determined by the River Leven Trustees according to a pre-agreed formula. There are also some licenced water abstraction points on the inflows to the loch; these are shown in Figure 3 and their waterbody identification numbers (WB_ID), locations and total allowable abstraction levels are shown in Table 1 Licenced water abstraction points on the inflows to Loch Leven and associated abstraction limits..

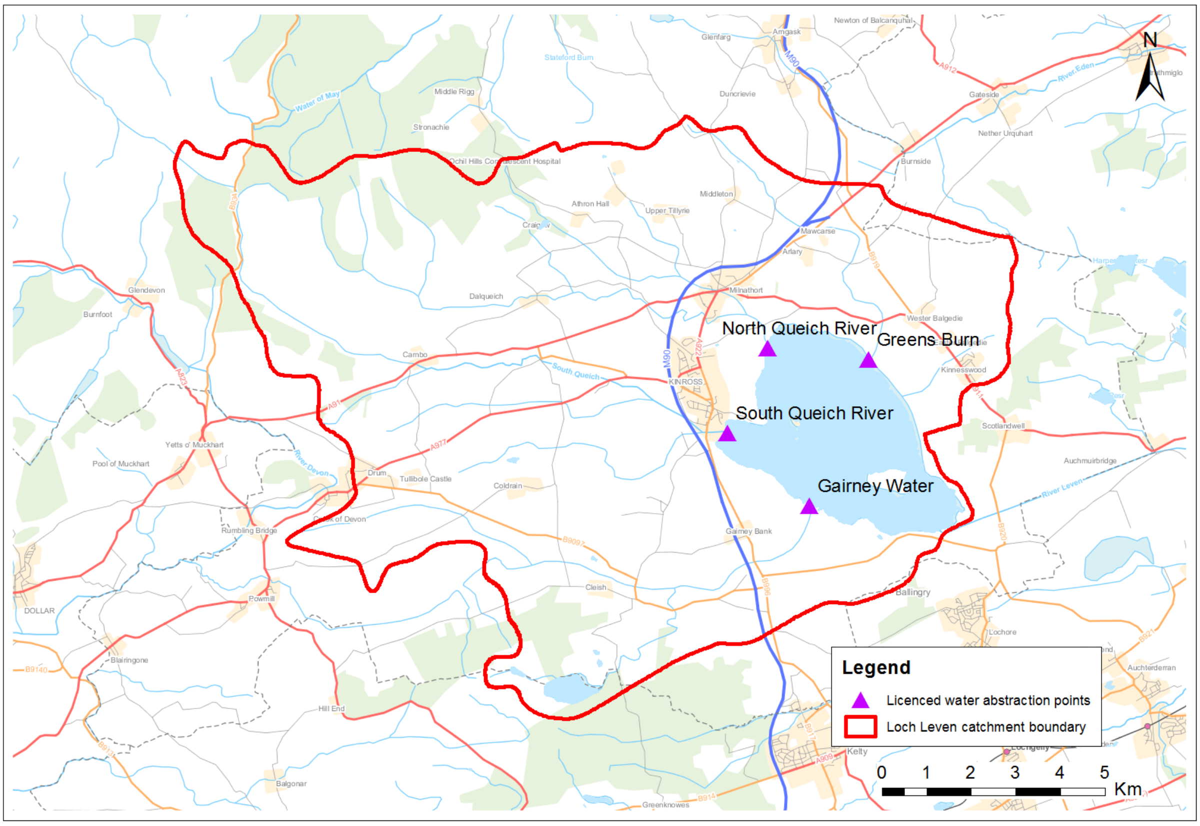


Figure 3 Catchment of Loch Leven showing licenced water abstraction points.

Table 1 Licenced water abstraction points on the inflows to Loch Leven and associated abstraction limits.

WB_ID	Location	Total (m^3y^{-1})	Total (m^3s^{-1})
6302	South Queich River	241,425	0.0077
6315	Gairney Water	418,096	0.0133
6316	Greens Burn	99,672	0.0032
6320	North Queich River	94,380	0.0030
Total		853,573	0.0271

After 19 years of operation, Sang (1872) reviewed options for further improvement of the water supply from the loch to the downstream mills. The most important of these were (1) increasing the capacity of the loch, and (2) increasing the catchment area of the loch. Sang (1872) concluded from his investigations that the volume of the loch should have been increased, rather than decreased, by the original works, but that it was ‘now’ too expensive to do that given that the sluice gates and sluice house would need to be rebuilt. He also concluded that increasing the size of the catchment (or “gathering grounds”) would require parliamentary approval, which was unlikely to be granted. So, the situation was left unchanged.

Smith (1966) summarised the annual hydrological balance of the loch since the building works were undertaken (Table 2). He also noted that, under average conditions, 80% of the evaporative losses from the lake surface take place during the summer.

Table 2 Annual water balance of Loch Leven (adapted from Smith, 1966)

Height of spillway crest above sea level	100 m
Water surface area at spillway	1.4 km^2
Volume of water below spillway	62.3 x 10^6 m^3
Mean water depth (volume/area)	4.3 m
Maximum water depth	25 m
Area of bed exposed per unit drawdown	230 ha. m^{-1}
Catchment area	145.4 km^2
Average rainfall	1050 mm y^{-1}
Average runoff	635 mm y^{-1}
Evaporation from loch surface	1.33 x evaporation rate from land
Flushing rate	1.7 loch volumes y^{-1}

Sargent and Ledger (1992) provide details of how the sluice gates operate, the role of the spillway and the measurement of water level in the loch and the way that these data are combined to estimate the amount of water discharged to the River Leven. These details are summarised below.

Five sluice gates, each 1.372 m deep and 2.718 m wide, were installed on the outflow from the loch. These gates are opened and closed manually using a screw lifting gear. Between 1850 and 1977, measurement of the sluice gate opening was recorded by a mechanical device that registered the number of turns of the screw (1 turn = 3.2 mm). In 1977, this mechanism was replaced by a Vernier gauge. Under normal conditions, the centre gate is kept closed. Prior to 1977, the water level behind the centre gate was measured at weekly intervals by manually reading a gauge board. Since then, water level has been measured by an electronic water level recorder.

The spillway is set at 1.373 m above the sluice sill (i.e. level with the top of the sluice gates when they are closed). The spillway is curved, with a straight line distance of 44 m between the ends of the curve. When the loch level is high, water flows over both the spillway and the closed central gate.

Using data collected between 1855 and 1985, Sargent and Ledger (1992) derived a depth storage relationship for the loch from its area at spillway level as calculated by Sang (1872) and the bathymetric survey data collected by Kirby (1971). The resultant volume/depth curve [see Sargent and Ledger (1992), Figure 3] was constructed from estimated changes in volume at different depths using steps of 50 mm.

Sargent and Ledger (1992) used the following equations to determine the level of discharge to the River Leven from under each sluice gate (Q_{ug} m^3 s^{-1}), over the spillway (Q_s m^3 s^{-1}) and over the sluice gates (Q_{og} m^3 s^{-1}).

Discharge under each sluice gate

$$Qug = C_{d} \times a\sqrt{(2gH)}$$

where:

C_d is the coefficient of discharge
a is the sluice gate opening height (m)
H is the head of water (m) (relative to the level of sluice gate sill)

and:

$$C_d = C_C \times \sqrt{[1 + C_c \times (a|H)]^{-1}}$$

where:

C_c is the coefficient of contraction, i.e. the ratio of depth at the *vena contracta* (i.e. the point in the stream of water where the diameter is at its minimum and the fluid velocity is at its maximum) to that under the sluice gate.

Discharge over the spillway

Discharge over the spillway was calculated as follows:

$$Q_s = 74.8 \times (H - 1.372)^{1.5}$$

Discharge over the sluice gates

Discharge over the sluice gates was estimated as follows:

$$Q_{og} = 5.0 \times [H - (1.372 + a)]^{1.5}$$

Total discharge

The total discharge from the loch (m^3 s^{-1}) was calculated as the sum of the above, as follows:

$$Q = Q_{ug} + Q_s + Q_{og}$$

Changes in water governance over time

The sluice gates are still operated by the River Leven Trustees. Over the years, a number of methods have been used for regulating the outflow from the loch. In 1965, Binnie & Partners proposed a new method of doing this and compared that to two previous suggestions, i.e. (1) Gourley's rules and (2) rules set out in a letter to Major Russell on 18 Feb 1965. They concluded that (1) would tend to keep the loch too full and that (2) would tend to keep the loch too empty.

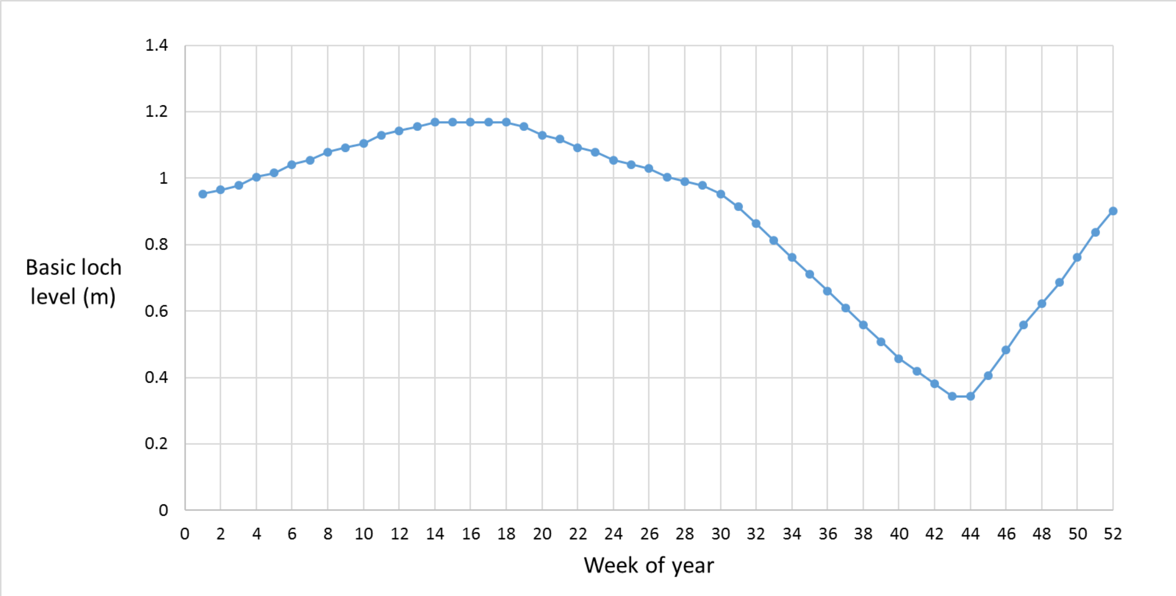


Figure 4 Weekly basic loch levels proposed by Binnie & Partners (1965).

Binnie & Partners (1965) suggested a series of loch levels, one for each week of the year (Figure 4), which should be achieved as closely as possible by managing the rate of discharge from the loch via the sluice gates.

They also proposed a set of 'Loch Regulation Rules', which can be summarised as follows:

1. If the loch is lower than the basic level, limit discharge to 1.4 $m^3 s^{-1}$.
2. If the loch is higher than the basic level, draw off water as required for power generation.
3. If the loch reaches the flood release level (1.22 m in March-May, or 1.19 m in other months) discharge as quickly as possible whilst keeping the river flow past Tullis Russell & Co. Ltd. to less than 21.2 $m^3 s^{-1}$.
4. During heavy rainfall when the loch level is high:
    a. discharge as quickly as possible, whilst not exceeding allowable river flow past Tullis Russell & Co. Ltd. (see above)
    b. maintain this elevated discharge for 12hours
    c. maintain maximum discharge if the loch level continues to rise and is likely to reach the flood release levels given in (3) within 24 hours
    d. otherwise, reduce the discharge to 5.7 $m^3 s^{-1}$

    The heavy rainfall and high loch levels for which the above action is considered 'appropriate' are as follows:

Loch level (m)	**Rainfall (mm d^{-1})**
≥ 0.76 - < 1.07	38
≥ 1.07	76

5. When snow and ice are present, the basic and flood release levels should be reduced by 300 mm for every 25 mm of water represented by the snow and ice, but only until water levels of 0.66 m and 0.71 m, respectively, are reached.

Binnie and Partners (1982) considered the effects of revising the rules proposed by Binnie and Partners (1965) to take into account the more recent sluice calibration results that had become available and the changing water requirements of downstream users (mill owners). They also aimed to provide reliable water supplies, maximise hydroelectric power (HEP) generation, and reduce the risk of floods around the loch shores, within the 'Cut' and further downstream at the factories. Based on a desk-based modelling study, and using updated loch outflow records that had been digitised by the Forth River Purification Board and the University of Edinburgh, the 1965 rules (Binnie & Partners, 1965) were found to be inadequate because they allowed the loch level to fall too low in winter. So, an updating of the criteria for ice was recommended. The authors also concluded that a flood release level of >1.14 m did not add significantly to the monetary value of the water for HEP, that maximum loch levels were not altered significantly by the different operating rules tested, that the number of days with very high water levels could be significantly reduced by lower flood level releases, and that there was capacity to release more water in late summer if a correspondingly lower release was accepted in early summer.

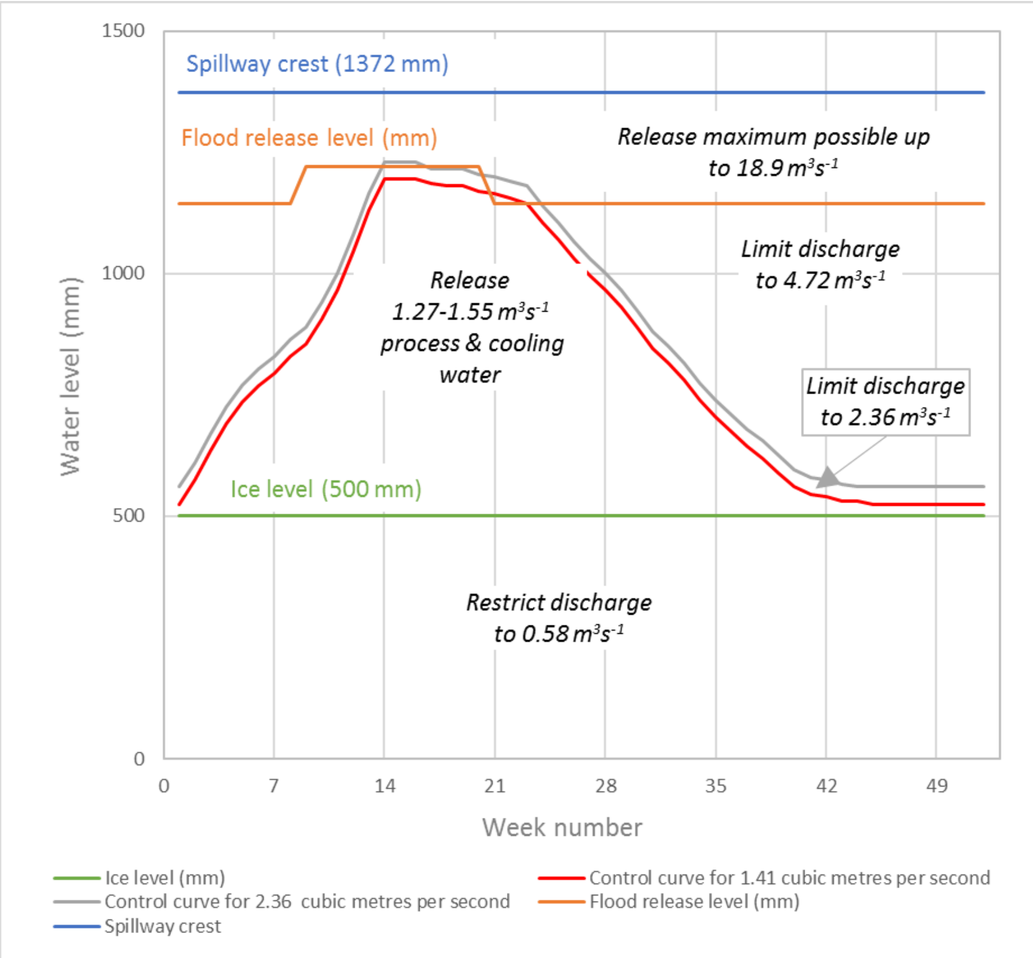


Figure 5 New operating rules suggested by Binnie and Partners (1982).

As a result of this review, new operating rules were suggested, as follows:

1. If the loch is below the ice level, restrict discharge to 0.58 m^3s^{-1}.
2. If the loch is between the ice level and the control curve for 1.4 m^3s^{-1} limit the discharge to 1.4 m^3s^{-1}, except between 1 May and 30 June (when discharge should be reduced by 10%, to 1.27 m^3s^{-1}) and between 1 July and 15 September (when discharge should be increased by 10%, to 1.55 m^3s^{-1}).

3. If the loch level is between the control curves for 1.41 m^3s^{-1} and 2.36 m^3s^{-1}, limit the discharge to 2.36 m^3s^{-1}.
4. If the loch level is between the control curve for 2.36 m^3s^{-1} and the flood release level, limit the discharge to 4.72 m^3s^{-1}.
5. If the loch level is above the flood release level, the discharge should be the maximum possible up to 18.9 m^3s^{-1}.
6. When snow and ice are present, the control curve and flood release levels should be reduced by 300 mm for every 25 mm of water represented by the snow and ice.

These new rules are illustrated pictorially in Figure 5.

Binnie and Partners (1982) also listed the main interests in the management and supply of water from Loch Leven as being downstream industry (in relation to power generation and water supply for industrial processes), farmers (in relation to flood protection) and nature conservation (food and habitat for protected species). They noted, in particular, that high water levels in March and April could detrimentally affect nesting birds, and that a sudden fall in water level when ice was present could drag ice down the shore, damaging rooted plants and scouring surface sediments. No concerns were noted in relation to water level and the fishery.

Operating the sluice gates under a Controlled Activities Regulation (CAR) licence

In 2017, the management of the sluice gates and the discharges from Loch Leven became the subject of a Controlled Activities Regulation (CAR) licence, which required approval from the Scottish Environment Protection Agency (SEPA). Under this agreement, the current water management regime was permitted to continue as outlined above, and operated by the River Leven Trustees. Additional requirements were put in place for the management and disposal of any accumulated sediment, the maintenance of the impoundment and the servicing and calibration of the related flow measuring equipment.

The current situation

The Loch Leven sluices continue to be operated by the River Leven Trustees in accordance with the recommendations of Binnie and Partners (1982), and taking into account the additional requirements of the recently agreed CAR licence. Although, originally, the management of the sluice gates was focused entirely on maintaining a secure water supply for downstream industry, especially during the summer months, more recently the ecological requirements of wildlife in and around loch and in the outflow, are starting to be taken into account. This is an important development because changes in water level of the loch can affect wildlife habitat and feeding grounds. For example, they can make it difficult for the Royal Society for the Protection of birds (RSBP) to control the level of the water table in the wet grassland that they manage for wading birds; this is a particularly important issue during the breeding season (Stoneman, *pers comm*.).

Future plans

Plans are being developed for the installation of electric lifting gear at the sluice gates to automate their management.

Acknowledgements

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